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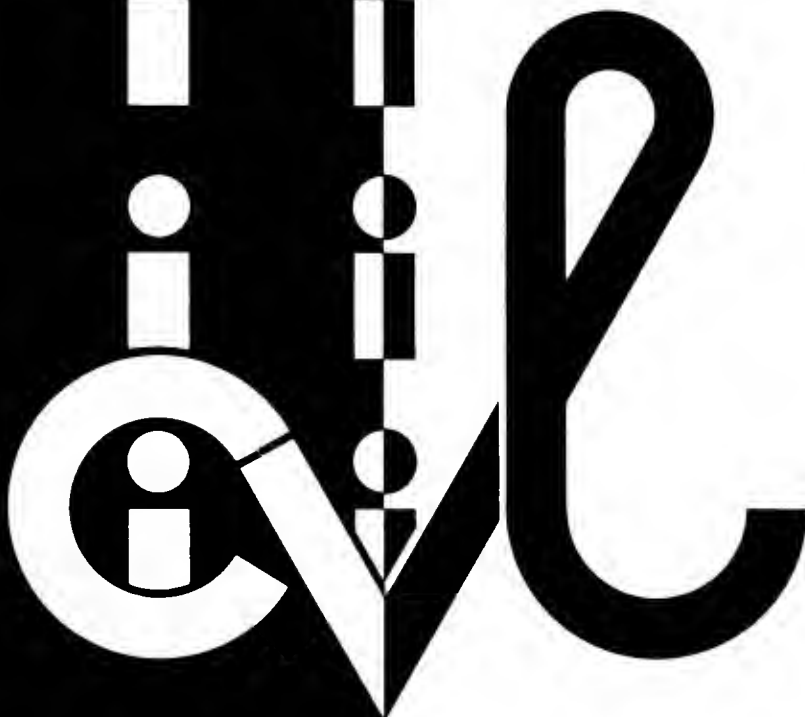
JOINT HIGHWAY RESEARCH PROJECT

Final Report

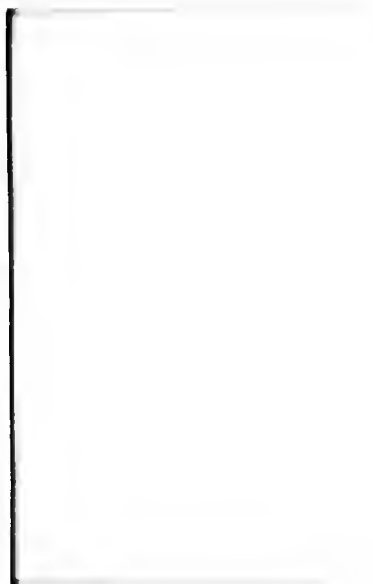
FHWA/IN/JHRP-92/13

THE USE OF ADVANCED TECHNOLOGIES
IN INDIANA DEPARTMENT OF
TRANSPORTATION

Thomas R. Kruse
Kumares C. Sinha



PURDUE UNIVERSITY



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THE USE OF NEW TECHNOLOGIES IN THE INDIANA DEPARTMENT OF TRANSPORTATION

Final Report

TO: Vincent P. Drnevich, Director
Joint Highway Research Project
FROM: Kumares C. Sinha, Research Engineer
Joint Highway Research Project

May 20, 1992
Revised September 9, 1992
Project No.: C-36-54TT
File No.: 3-3-46

Attached is the Final Report on the HPR Part II Study titled, "The Use of New Technologies in the Indiana Department of Transportation." The study included a survey of state transportation agencies, interviews with INDOT personnel and personnel of other state transportation agencies, and a workshop conducted with the executive staff of INDOT. Suggestions for the development of a new technology program within INDOT were also made.

This report is forwarded for review, comment and acceptance by the INDOT and FHWA as fulfillment of the objectives of the study.

Respectfully submitted,



K. C. Sinha
Associate Director

KCS/rtp

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Final Report

THE USE OF ADVANCED TECHNOLOGIES IN INDIANA
DEPARTMENT OF TRANSPORTATION

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ABBREVIATIONS

AASHTO: American Association of State Highway and
Transportation Officials
ADIS: Advanced Driver Information Systems
ADT: Average Daily Traffic
AI: Artificial Intelligence
ATIS: Advanced Traveler Information Systems
ATMS: Advance Traffic Management Systems
ATR: Automatic Traffic Recorder
AVI: Automatic Vehicle Identification
AVC: Automatic Vehicle Classification
AVCS: Advanced Vehicle Control Systems
AVL: Automatic Vehicle Location
CADD: Computer Aided Drafting and Design
CVO: Commercial Vehicle Operations
DOD: Department of Defense
DOT: Department of Transportation
FHWA: Federal Highway Administration
FTMS: Freeway Traffic Management Systems
GIS: Geographic Information System
GPS: Global Positioning Systems
HAR: Highway Advisory Radio
HELP: Heavy Vehicle Electronic License Plate
HIS: Highway Information Systems
IVHS: Intelligent Vehicle/Highway Systems
MIS: Management Information System
NGS: National Geological Survey
OBC: On-Board Computers
PC: Personal Computer
PMS: Pavement Management Systems
R&D: Research and Development
RFP: Request For Proposal
TRB: Transportation Research Board
TWC: Two-Way Real Time Communications
UTCS: Urban Traffic Control Systems
VIP: Video Image Processing
VMT: Vehicle-Miles of Travel
VPH: Vehicles Per Hour
WADS: Wide Area Detection Systems
WAN: Wide Area Network
WIM: Weigh-In-Motion

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CHAPTER 1: INTRODUCTION

The use of computer and related technologies has increased rapidly during recent years, fostering advances in information management, automation, and communications that significantly impact our way of life. Computers have become an integral part of many professions, including engineering, business, science, and medicine. They continually evolve, becoming smaller, faster, cheaper, and more powerful with improved data storage capabilities.

As computers evolve and usage increases, new applications are discovered, expanded upon, and adapted to engineering and other practices. Extensive hardware and software industries have formed which develop and market a wide variety of products for applications. These computer-related advanced technologies are changing the way professions are practiced.

State transportation agencies can benefit greatly from advanced technologies. The data intensive nature of the transportation profession and the large amount of resources allocated to transportation in the U.S. make these agencies especially amenable to the use of advanced technologies.

Transportation agencies are primarily concerned with the planning, design, construction, maintenance and operation of street and highway facilities. Presently they face rising congestion, increased costs, and heightened environmental concerns. Advanced technologies can increase efficiency and

productivity, reduce labor needs, and improve traffic management capabilities to help alleviate these problems.

Many new technologies have already been proven to be cost effective and productive. These technologies are being widely pursued by many state transportation agencies. For example, database management, Computer Aided Drafting and Design (CADD), and automatic traffic data collection programs have been adopted in most states.

Other technologies such as Intelligent Vehicle Highway Systems (IVHS), robotics in construction and maintenance, and video image processing are not yet considered state-of-the-art. These technologies are only being actively pursued in a few states.

Each state approaches advanced technology differently. Some states are at the forefront, developing as well as implementing technologies as they appear. Other states prefer to wait until a technology has been proven to work and has most defects corrected before they will implement it into their organization. The rest of the states fall into the area in between. They will follow the forerunners closely, implementing those technologies that have worked in other states, but may not yet be proven state-of-the-art (Hoel 1985).

Two leaders in the application of advanced technologies are the California and Michigan transportation agencies. These states have successfully implemented many new technologies and are leaders in research and development (R&D) as well.

The California Department of Transportation (Caltrans) has an Office of New Technology within the Division of Transportation Planning that evaluates advanced technologies and recommends their implementation (Sinha et al. 1988). The Michigan Department of Transportation has a unique managerial strategy in which individuals are selected to "champion" various new technology projects. Other leaders in the use of advanced technologies are Minnesota and Texas.

Successful implementation of advanced technologies requires careful planning and management. It generally involves high initial capital costs, agency reorganization, and the retraining of personnel. Resources must be shifted from labor intensive procedures to more technical procedures. The increased productivity of new methods must outweigh capital, training, management, operation, maintenance, administrative, and conversion costs.

States that have taken the lead in adopting advanced technologies have adjusted organizational frameworks, shifted resources, and developed procedures to systematically evaluate and implement such technologies. They have benefited from increases in productivity as a result. Many states have not taken these steps and have not received the full benefits that advanced technologies offer. This project demonstrates how advanced technologies can be successfully applied in transportation agencies.

1.1 State Agency Survey

A questionnaire was sent to state transportation agencies

to determine which advanced technologies are being used, what applications they are used for, which are the most productive, and what problems are encountered when implementing advanced technologies. Both research and development projects and existing applications were investigated. The results were compared to a survey done in 1985 by the Virginia Department of Highways to determine which areas are growing most rapidly. An extensive literature review was also made to define the various advanced technologies.

1.2 Implementation Guidelines

Several of the technologies identified in the state agency survey were selected for a more detailed analysis. This involved a more detailed description of each of the technologies, identification of applications states are pursuing in each area, a discussion of the benefits and costs of each technology, and development of general guidelines for successful implementation of each technology.

Each technology was discussed and defined in greater detail than in the previous step. This was done through literature review and interviews with INDOT personnel, university researchers and vendors that have expertise in these areas. Information from the state agency survey and the literature review was used to develop a list of applications within state transportation agencies where the technologies have been found to be beneficial.

This was followed by development of general guidelines for implementation of these technologies within a state

transportation agency. The guidelines were demonstrated by applying them to the Indiana Department of Transportation (INDOT) to recommend courses of action by which INDOT can better use advanced technologies.

It must be remembered that the primary thrust of this study was to outline procedures for implementing advanced technologies within INDOT. Thus it is necessary to view these technologies within the context of INDOT. In order to relate the general requirements obtained from other state agencies and literature review to INDOT, the status of the use of each of the advanced technologies within INDOT was identified and compared with the general requirements to develop activities for INDOT to pursue. To this end, the study (1) identified advanced technologies that INDOT is interested in, (2) assessed the current status of each of these technologies within INDOT, and (3) developed initial recommendations of courses of action for INDOT to follow in each area.

After the initial phase of the study, a workshop was held with the executive staff and other senior personnel of INDOT. Summary papers were made available to the participants in each of the ten identified areas. The workshop and the papers provided an excellent resource for checking the general requirements to see how they relate to INDOT. The workshop also led to the identification of other personnel to be interviewed within INDOT, university researchers, and other agencies. These interviews were used to estimate the costs and benefits of different applications. In some cases, vendors of various advanced technologies were contacted to

help estimate the costs.

The analysis of each technology is placed in a separate chapter of this report. Separate assessments were done in each of the following areas:

- * Computer Aided Drafting and Design (CADD),
- * Geographic Information System (GIS),
- * Advanced Surveying Technologies,
- * Expert Systems,
- * Computer Models in Planning and Programming,
- * Quality Assurance,
- * Robotics and Automation,
- * Intelligent Vehicle/Highway Systems (IVHS).

Each chapter defines appropriate technologies, lists possible applications, identifies the general requirements for successful implementation of the various technologies, discusses the status of these advanced technologies within INDOT, applies the general requirements to INDOT to develop a program for INDOT to follow and discusses the costs and benefits of each technology, where possible.

1.3 A New Technology Program

Key factors in the development of an overall advanced technology program were identified. Then the findings from the previous research were used to suggest such a program for INDOT.

Each area of new technologies identified for further analysis was discussed separately, and a phased implementation plan was developed in each area. The implementation plan was

divided into three phases: near term (1-2 years), mid term (3-5 years), and long term (6-10 years.). Projects to be pursued during each phase were listed and described.

An incremental approach was applied, whereby projects build upon previous efforts. Demonstration projects were also stressed, in which an agency starts slowly to demonstrate and gain experience with a technology before full scale implementation.

After the phased plans for each area were developed, the organizational aspects of an advanced technology program were discussed, and suggestions for a possible organization to create a new technology program were presented.

CHAPTER 2: STATE AGENCY SURVEY

Before a new technology can be selected, it is necessary to identify and compare with other available technologies. This will help insure that the most cost effective alternative is selected. Furthermore, care must be taken to insure that the chosen action will not interfere with the application of other technologies that may become available in the future. For example, a traffic database system that is not set up properly may interfere with future GIS applications. Thus it is also important to be aware of emerging technologies, even when they may seem unrelated at first glance.

In April 1989, with the help of AASHTO, Purdue University mailed a questionnaire to each state transportation agency to determine the status of their applications of advanced technologies. Forty-two states and Puerto Rico returned surveys. This chapter summarizes the survey results in order to identify available and emerging technologies and gain insight into which technologies have been found most beneficial among the states.

Survey respondents were asked to describe their level of use of new technologies, list R&D projects in various high technology areas and rate the expected costs and benefits of other existing or planned high technology projects. They were

also asked to list current applications of advanced technologies, possible barriers to the use of advanced technologies and areas they felt had high potential to benefit from advanced technologies. The surveys are summarized by question in the following sections, and are compared to results from a similar survey conducted in 1985 by the Virginia Department of Highways and Transportation. A copy of the Purdue survey is included in Appendix A.

2.1 Level of Use of Advanced Technologies

The agencies responding to the survey were first asked to categorize their level of use of advanced technologies. The results indicated that there is a great deal of interest in advanced technologies. Of the agencies responding to the questionnaire, 86% stated that they had already applied some advanced technologies and 14% were planning to apply advanced technologies. All agencies were planning to apply advanced technologies.

2.2 Research and Development (R&D) Activities

Respondents were asked to list R&D projects in the following high technology areas:

- * Geographic Information Systems (GIS),
- * Computer Applications,
- * Real Time Traffic Control,
- * Expert Systems,
- * Intelligent Vehicle/Highway Systems (IVHS),
- * Automatic Vision and Image Processing,
- * Robotics in Construction and Maintenance, and
- * Other.

These are primarily new areas that Virginia's 1985 study,

discussed later, did not address. Most agencies listed some R&D projects involving advanced technologies. Only 9% (four states) stated that they had no current R&D projects or that they did not participate in R&D but just bought available products.

Both in-house R&D efforts and consultant projects were considered to be R&D by most states. In some cases, states described activity in a given area that they did not consider to be formal R&D. "Non R&D" projects were included with the R&D projects because the total number was small and similar projects were considered to be R&D by other states. Other states stated that they had R&D projects but did not describe them. The results are summarized in Table 2.1, and are further broken down by area in the sections that follow.

2.2.1 Geographical Information Systems (GIS)

Geographical Information Systems is an emerging technology; thus, exact definitions are hard to find. In general, GIS combines the computerized mapping facilities of Computer Aided Drafting and Design (CADD) packages with intelligent databases. Map data is transferred into CADD format manually or by digitizing maps, and it is then possible to connect coordinates on the map with particular information in the database.

Table 2.1: Present Research and Development Projects

| Area | % of States With Projects |
|--|------------------------------|
| Geographic Information Systems (GIS) | 69% |
| Computer Applications | 65% |
| Automatic Vision and Image Processing | 30% |
| Real Time Traffic Control | 28% |
| Intelligent Vehicle/Highway Systems (IVHS) | 26% |
| Expert Systems | 23% |
| Robotics in Construction and Maintenance | 9% |

These systems can incorporate different layers of information on topography, utilities, soil types, traffic, streets, political boundaries and many other types of useful information. Once a GIS has been created, it can be shared by many departments, and can constantly be updated as changes are made.

Some companies and government agencies offer already digitized geographic data from satellites, surveys, aerial photographs and other sources. Global Positioning Systems (GPS) can also be used to develop base geographic data. This involves the use of satellites, as opposed to traditional surveying methods, for locating and fixing points. In fact, due to the emerging nature of GIS, distinctions between database management, GIS, GPS, and CADD are somewhat blurred. Some of the states that were surveyed placed all or some of these technologies under the GIS heading.

A total of 69% of the states reported activity in the GIS area. Most states (55%) considered this activity to be R&D, while 14% did not. Of the states that did not consider their GIS activity to be R&D, 7% described working GIS systems and

the remaining 7% were pursuing GIS to some degree but had no "formal" R&D projects.

Most of the states pursuing GIS were involved in the implementation process, but activities ranged from initial feasibility studies to working systems. A variety of databases were listed for use with these systems. These included databases containing trip generation rates, growth rates, employment rates, population, traffic data, geometric data, pavement and bridge condition data, program monitoring data, accident data, signal inventory data, mileposts, and construction site information.

2.2.2 Computer Applications

Computer technology is the basis for all of the advanced technologies discussed in this paper. With the continued use and development of computers, new applications for computers in transportation are continually invented and other applications are improved. These applications include database management, laboratory and field data collection and analysis, construction management and quality control, and computer aided planning and design (including CADD).

Several states listed projects under the heading "Other" that other states had included in the "Computer Applications" category. These projects all involved computers to some degree. Therefore, projects listed under the heading "Other" were included with "Computer Applications" in this section.

Sixty-five percent of the states listed R&D projects in computer applications, and this category contained the most

R&D projects by far. A few states did not list each project, because of the large amount of projects they were pursuing. One state listed over sixty separate projects.

Table 2.2: Computer Applications R&D Projects

| Category | % of States With Projects |
|--|------------------------------|
| Computer Aided Planning and Design | 35% |
| Project/Program Scheduling/Management | 23% |
| Maintenance Management | 19% |
| Computer Inventories | 16% |
| Advanced Survey Positioning Systems | 14% |
| Computer Networking and Communications | 14% |
| Construction and Preconstruction Management | 14% |
| Database Management Systems | 14% |
| Executive Information Systems | 14% |
| Financial Management | 14% |
| Safety Applications | 12% |
| Lab, Materials, and Research Management | 9% |
| Photo/Video Logging | 9% |
| Computer Aided Software Engineering | 7% |
| Contract and Bid Analysis and Management | 7% |
| Non-destructive Testing of Roads and Bridges | 7% |
| Vehicle Licensing and Permits | 7% |
| Computer Simulation of Driving Conditions | 5% |
| Photogrammetry | 5% |
| Remote Monitoring of Bridges | 5% |
| Weigh-In-Motion | 5% |

The projects were grouped into several categories to determine the areas in which the most activity is occurring. There was some overlap between these categories, but they still give a general idea of the areas being most actively pursued at present. The categories and percent of agencies with projects in these categories are listed in Table 2.2.

The four areas with the most activity were Computer Aided Planning and Design, Project or Program Scheduling and Management, Maintenance Management, and Computer Inventories.

Computer Aided Planning and Design involved both CADD projects and planning applications. All of the states included in this category listed CADD projects, and 13% listed transportation planning applications. CADD projects listed ranged from initial implementation to plans to further develop existing systems. Both drafting and design applications for bridges and roadways were mentioned.

Applications listed under Project or Program Scheduling and Management ranged from critical path scheduling to comprehensive program management information systems involving several databases. There is some overlap between the Project/Program Scheduling/Management and Construction and Preconstruction Management Categories. Projects listed in these two categories were very similar, and were separated on the basis of the terminology used by the state answering the questionnaire. The main difference between the two categories is that projects listed under Construction and Preconstruction Management involved applications designed for field engineers using PCs.

The Maintenance Management category included several activities that dealt with maintaining and managing bridges, pavements, equipment, and signal controllers. These activities included maintenance budgeting and tracking, databases for inspection records, maintenance contract management, and comprehensive Pavement Management Systems (PMS).

Computer Inventories involved database inventories of facilities. These facilities included signals, signs,

bridges, buildings, highways, and even videolog inventories of roadways. Most were relational databases in which different types of data could be held in separate databases and linked by location or some other key. The difference between the Computer Inventories and Database Management categories is that the Database Management category contains R&D projects involving development of comprehensive data management systems, as opposed to individual applications.

It is not possible to discuss each category and project here because of the large volume of projects. Some of the more unique projects were a voice input/output system, notebook computers for field engineers, simulation of driving conditions or accidents using interactive graphics, and an interactive, real time hydraulic analysis system.

2.2.3 Automatic Vision and Image Processing

Automatic Vision and Image Processing involves the use of computers to collect and analyze video data. It can be applied in many areas, including pavement distress identification and traffic surveillance.

In pavement distress identification, the use of cameras mounted on moving vehicles to collect video data of the road surface condition replaces the time consuming task of manual data collection. This video data can then be analyzed by computer, thus removing human subjectivity from the evaluation process.

If used for traffic surveillance, video image processing

could be simultaneously used to detect traffic, take traffic measurements, perform surveillance, detect incidents, and recognize special vehicles. Such traffic data collection systems, also called Wide Area Detection Systems (WADS), have been used successfully in Japan but have not been fully developed and tested.

The video cameras used in WADS can cover all lanes of a given roadway, in a single direction. Thus numerous side-by-side detection devices that disturb the pavement are not required, making the systems more mobile and cheaper to maintain than traditional loop detection systems. Traffic flow parameters can also be measured over distance instead of at points, because the cameras can cover large longitudinal segments of the roadway. Furthermore, the cameras in a WADS system can be used for visual inspection of traffic and incidents by personnel in the traffic operations center.

Thirty percent of the states (13 agencies) listed R&D projects under this heading. Projects in 11% of the states (5 agencies) involved scanning, image text retrieval, or automatic generation of contract plans. Of the remaining 19% (8 states), 12% (5 states) were developing video traffic data collection systems. Other R&D projects were video image processing for vessel registration in Hawaii, visual simulation of proposed construction sites in Illinois, digital image processing of hardened concrete specimens in Virginia, and video imaging for evaluating pavement surface distress in Ohio.

2.2.4 Real Time Traffic Control

The widespread adoption of vehicle detection equipment in recent years has made real time traffic control possible. Real time traffic data, often sent through a computerized traffic control center, is used to change traffic signal timings to respond to changes in traffic volumes, identify and respond to incidents, and manage traffic on arterials, freeways, and corridors.

Several urban areas throughout the country are utilizing or developing Freeway Traffic Management Systems (FTMS) that operate in real time. These systems incorporate adjustment of ramp metering rates and signal timings on adjacent arterials, incident detection and response, and highway information systems and user communications to reduce congestion on freeways (TRB 1987; McDermott 1989; Bridges 1990).

Highway information systems and user communications refer to methods used to communicate travel information (congested areas, alternate routes, etc.) to drivers (Hoel 1985). Available methods include variable message signs, Highway Advisory Radio (HAR), commercial radio and television, and dial up phone lines. FTMS have been found to be effective in improving traffic conditions during peak hours.

Intelligent Vehicle/Highway Systems (IVHS) is another area that involves real time traffic control, as discussed in Section 2.4. Therefore some states included real time traffic control projects under the IVHS heading. Many states with existing or planned FTMS listed the driver information portions of the FTMS projects under real time traffic control.

One state also listed the real time traffic control application of video image processing here. A total of 28% of the states listed R&D projects in this area. FTMS applications were listed 10 times (23%), while Urban Traffic Control Systems (UTCS) were mentioned by two states, and microcomputer based control systems that could provide UTCS functions for less cost were being developed in three states. Some of the states listed already completed R&D projects.

A variety of applications of the above systems were mentioned, including controlling traffic on arterials, freeways, diamond interchanges, and frontage roads. Other projects listed included an electronic dust storm warning system in Arizona, red light cameras to detect traffic signal violators in Minnesota, research on real time traffic management algorithms in Michigan, development of a simulator for advanced traffic control testing and training in California, and detector driven traffic controllers that can be monitored or altered via remote microcomputers and phone lines.

2.2.5 Intelligent Vehicle/Highway Systems

Intelligent Vehicle/Highway systems is an umbrella term encompassing several technologies used to improve the efficiency of transportation systems by reducing delay and congestion, enhancing driver safety, improving timeliness of goods delivery, and preserving mobility. IVHS incorporate several advanced technologies, including real time traffic control, Automatic Vehicle Identification (AVI), Automatic

Vehicle Location (AVL), Weigh-In-Motion (WIM), On-Board Computers (OBC), and Two-Way Real Time Communications (TWC). These technologies, along with others, have been used to develop four major applications areas: Advanced Traffic Management Systems (ATMS), Advanced Driver Information Systems (ADIS), Fleet and Freight Control Operations, and Advanced Vehicle Control Systems (AVCS). These applications are defined in the following paragraphs, followed by a summary of survey results.

Advanced Traffic Management Systems (ATMS) are very similar to the FTMS discussed previously, and provide tools for improving operational efficiencies and managing demand on transportation networks. They extract relevant traffic flow data from traffic detection systems and use this information to automatically implement appropriate traffic control strategies such as modification of signal timings and ramp metering rates, incident detection and response, and informing drivers using highway information systems and user communications.

Advanced Driver Information Systems (ADIS) are used to present up-to-date travel information to motorists to aid in navigation. This information can include congestion locations, weather and road conditions, lane restrictions, and tourist information. ADIS is very similar to the highway information systems mentioned in Section 2.2.3, but can involve more sophisticated technologies.

In recent years a number of on-board navigation aids have been developed based on OBC and AVL. These technologies can

include on-board replication of maps and signs, pre-trip electronic route planning, traffic information broadcasting systems, and electronic route guidance systems. Real time traffic information and vehicle location can be used to determine the quickest route for the driver to follow. Vehicle location can be determined using on-board compasses and odometers that measure the direction and distance traveled from a known point (self contained/dead reckoning systems), or through the use of sophisticated triangulation techniques involving radio waves from towers and/or satellites (e.g. GPS, LORAN-C and GEOSTAR).

AVL and OBC can also be used, along with AVI, WIM and TWC, for Freight and Fleet Control Operations. These technologies have the potential to provide significant benefits to freight carriers, state and local governments, and the public.

AVI involves the use of an interrogator/receiver built into the roadway and an electronic license plate or transponder tag attached to the vehicle that can be read via light, radio waves, or microwaves. If used with WIM, delay at truck weigh stations and state expenditures for weight enforcement could be greatly reduced. Vehicles can automatically be identified, classified, weighed, and checked for roadway/bridge compliance as they drive through weigh stations. Even if WIM was not accurate enough for enforcement, truck traffic data collection for cost allocation and planning could be greatly improved. Currently several states are involved in the Heavy Vehicle Electronic License

Plate (HELP) program, also known as the Crescent Study, which is testing AVI and WIM for truck monitoring.

AVI technology may also offer benefits to private automobiles. Tests of AVI for automatic toll collection at toll plazas have been done in California (Bushey 1989), and AVI could also be used to develop congestion pricing to reduce travel during peak hours, or to check compliance with hours of service regulations.

OBC technology can monitor a truck's operating system and notify the operator of any problems. In addition, OBC systems can automatically record vital travel information such as mileage, speeds, fuel consumption, and the time and date when a truck passes certain landmarks. The OBC would enable truck drivers to access information such as delivery instructions or road maps.

AVL can be used by the dispatcher to track each vehicle's location at regular time intervals, thus allowing dispatchers to efficiently schedule pick-up or delivery changes. TWC provides communication between the truck driver and dispatcher whenever required. These technologies would also be useful for public service vehicles such as police and ambulance fleets.

Advanced Vehicle Control Systems (AVCS) are vehicle and/or roadway based electro-mechanical and communications devices that enhance vehicle control. They include radar braking, automatic headway control, automatic lane keeping, machine vision, and even complete replacement of the driver using electrified highways. These electrified highways are

being investigated by the California Department of Transportation (Bushey 1989). AVCS technologies have the capability of greatly increasing roadway capacities, operating speeds, and safety within existing highway right-of-ways.

Twenty-six percent of the agencies surveyed reported current R&D projects involving IVHS. There was some overlap between IVHS and real time traffic control, with states listing very similar projects in the different areas.

Several states listed the HELP project for evaluating AVI and WIM for monitoring heavy vehicles. Other projects included automatic toll collection in California, on-board navigation systems in Illinois and California, commercial vehicle operations in Michigan, AVCS in California, automated highways in California, and ADIS in several states.

2.2.6 Expert Systems

Knowledge-based expert systems refers to a type of computer software that evolved from research in artificial intelligence, which attempts to make decisions by recreating the necessary knowledge base. Information input into the computer is compared to a database of knowledge, from which the computer generates possible courses of action for the given situation.

An example is the French ERASME system (Antoine et al. 1990) for pavement rehabilitation. Once data on pavement structure, distress, traffic, and deflection characteristics are input into the system, ERASME can generate rehabilitation strategies.

Other possible applications include facility design, materials selection, bridge management, construction management, and selection of traffic signal control plans given real time traffic information. The primary advantage of these systems is they can reproduce a lengthy decision making process in a short time, even when an expert is not available.

Twenty-three percent of the states (10 agencies) reported activity in the area of expert system, with thirteen projects listed and described. Applications included pavement maintenance systems, highway rehabilitation systems, highway safety analysis advising, noise barrier design, bridge repair priority determination, crash attenuator design, traffic and road condition data reduction, selection of training methodologies for Portland Cement Concrete quality assurance personnel, and hazardous waste management.

One example of these applications is an expert system used in Wisconsin to identify pavement conditions and select an optimum pavement management program for a group of roads. Another example is an expert system in Minnesota that selects truck routes, assesses tolls, and issues permits, while taking into account seasonal road restrictions, bridge limits, overpass heights, high traffic areas, and construction areas.

2.2.7 Robotics in Construction and Maintenance

While the use of robotics in manufacturing has been widely adopted, widespread introduction of automation in facility maintenance, facility construction, and vehicle maintenance has not occurred. Yet, construction and

maintenance could benefit greatly from automation. Potential benefits include productivity improvements, cost savings, quality improvements, and increased work force safety. Possible applications include automated pothole repair, crack sealing, line painting, road grading, and the servicing of maintenance and construction vehicles.

Only 9% of the states surveyed (4 agencies) reported current R&D projects in the robotics area. There were a total of eight projects being developed. California had 5 projects underway to develop prototype systems for automated pavement marker placement, crack sealing, bag pick-up, litter retrieval, and paint striping equipment. The other projects were an automated highway photolog laser videodisc retrieval system in Connecticut, a remote-control maintenance truck in Minnesota, and an automated weather sensing system to help determine when to use snow removal equipment in Wisconsin.

2.3 Applications and Perceived Costs and Benefits

Survey respondents were next asked to describe their use of computer and advanced technologies in the following areas:

- *Database Management,
- *Automated Pavement and Bridge Distress Sensing Systems,
- *Travel Monitoring and Counting,
- *Arterial Traffic Operations and Management,
- *Highway Information Systems and User Communications,
- *Computer Aided Planning and Design,
- *Laboratory and Field Data Collection and Analysis,
- *Construction Management and Quality Control,

*Advanced Survey Positioning Systems, and

*Other.

They were also asked to describe their expected costs and benefits in these areas as high, low, or none. Both actual and planned projects were included, but not all agencies responded in each area. The resulting rankings of costs and benefits are summarized in Table 2.3, where Percent Responding refers to the percent of agencies, out of the 43 answering the survey, that responded in the given area.

It is important to remember that categorizing costs and benefits as high or low involves some subjectivity on the part of the respondent. Furthermore, whether a cost is high or low depends on the economic base of the agency and the extent to which the agency is involved with the technology. Demographics can also play a role. For example, a less populated state could be expected to benefit less from advanced technologies in arterial traffic operations and management because congestion is less likely to be a problem in that state. In addition, the cost of such technologies could be rated higher because there is less of a tax base to draw on for funding, and perceived costs could also depend on the extent of involvement (e.g. PC or mainframe based systems).

Table 2.3: Perceived Costs and Benefits

| | |
|---|-----|
| Database Management: | |
| Percent Responding | 88% |
| High Cost, High Benefit | 50% |
| Low Cost, High Benefit | 50% |
| Automated Pavement and Bridge Distress Sensing Systems: | |
| Percent Responding | 77% |
| High Cost, High Benefit | 27% |
| High Cost, Low Benefit | 3% |
| Low Cost, High Benefit | 15% |
| Low Cost, Low Benefit | 9% |
| No Cost, No Benefit | 3% |
| No Plan to Use | 42% |
| Travel Monitoring and Counting: | |
| Percent Responding | 88% |
| High Cost, High Benefit | 21% |
| High Cost, Low Benefit | 3% |
| Low Cost, High Benefit | 61% |
| Low Cost, Low Benefit | 8% |
| No Plan to Use | 8% |
| Arterial Traffic Operations and Management: | |
| Percent Responding | 74% |
| High Cost, High Benefit | 22% |
| Low Cost, High Benefit | 31% |
| No Plan to Use | 47% |
| Highway Information Systems and User Communications: | |
| Percent Responding | 79% |
| High Cost, High Benefit | 29% |
| High Cost, Low Benefit | 6% |
| Low Cost, High Benefit | 26% |
| Low Cost, Low Benefit | 6% |
| No Plan to Use | 32% |
| Computer Aided Planning and Design: | |
| Percent Responding | 91% |
| High Cost, High Benefit | 67% |
| High Cost, Low Benefit | 5% |
| Low Cost, High Benefit | 23% |
| Low Cost, Low Benefit | 3% |
| No Plan to Use | 3% |
| Laboratory and Field Data Collection and Analysis: | |
| Percent Responding | 86% |
| High Cost, High Benefit | 19% |
| High Cost, Low Benefit | 5% |
| Low Cost, High Benefit | 54% |
| Low Cost, Low Benefit | 3% |
| No Plan to Use | 19% |

Table 2.3, Continued

| | |
|--|-----|
| Construction Management and Quality Control: | |
| Percent Responding | 77% |
| High Cost, High Benefit | 18% |
| High Cost, Low Benefit | 9% |
| Low Cost, High Benefit | 48% |
| Low Cost, Low Benefit | 3% |
| No Plan to Use | 21% |
| Advanced Survey Positioning Systems: | |
| Percent Responding | 81% |
| High Cost, High Benefit | 17% |
| High Cost, Low Benefit | 14% |
| Low Cost, High Benefit | 40% |
| Low Cost, Low Benefit | 3% |
| No Plan to Use | 26% |

However, the rankings of costs and benefits can still give a general idea of the areas being most widely pursued and the areas providing the highest benefits. Survey results are broken down by area in the sections that follow.

2.3.1 Database Management

Database management was the applications area with the second highest level of activity, with 84% of the agencies listing projects. It was also the only applications area where zero percent of the states indicated "No Plan to Use" advanced technologies. The database applications most commonly listed were computer inventories (e.g. road, bridge, sign, signal) (33% of agencies), pavement and bridge management (28%), relational/integrated databases which can tie separate databases together using location or some other key (25%), project/program management (19%), GIS (14%),

financial management systems (14%), and overall MIS or database system restructuring (12%).

Of the above applications, GIS and relational or integrated databases are very similar. GIS are based on integrated databases, and a few states indicated that building relational databases now was a first step in future GIS applications. Combining these two areas would give a total of 39% of the states pursuing integrated database technology, making this the most frequently mentioned application of database technology. Also, two states listed highway characteristics inventory applications under the heading Highway Information Systems and User Communications but not under Database Management. These were included in this section as computer inventories.

All of the states responding perceived high benefits associated with database management technology. However, half of them perceived their systems to have low cost and the other half perceived high costs. This disparity is probably due to the high variation in degree of involvement between agencies. The degree of involvement ranged from small personal computer applications to mainframe applications involving CADD and GIS. Other applications listed included construction management, materials management, equipment management, personnel management, and traffic/accidents databases.

2.3.2 Automated Pavement and Bridge Distress Sensing

This is the applications area with the least activity, as

only 40% of the agencies listed projects and 42% of the responding states indicated they had no plan to use automated pavement and bridge distress sensing technologies. Most of the projects listed under this heading involved using vehicles equipped with computers to collect data for various combinations of pavement roughness, rutting, geometry, skid resistance, and deflection basins. The sensing systems used to measure these data involved laser, video image processing, and acoustic sensors. Other applications listed involved the monitoring of corrosion or strain in bridges.

Some states listed similar pavement distress sensing systems under the heading "Laboratory and Field Data Collection and Analysis". When projects listed under these two headings are combined, 30% of the states listed projects involving pavement condition sensing from moving vehicles, and only 7% listed bridge monitoring applications.

2.3.3 Travel Monitoring and Counting

Travel monitoring and counting technologies were some of the most widely used technologies, and were also perceived to be very cost effective. Of the 88% of states responding in this area, 61% perceived automated travel monitoring and counting technologies to have low cost and high benefit. This is higher than any other applications area. Eighty-one percent (81%) of the states listed and described projects in this category.

The descriptions of applications and planned projects

indicated widespread use of automatic counting systems equipped with automatic vehicle classification (AVC), speed sensing, telemetry, and WIM equipment. Use of microcomputers to store and collect data for later uploading to a mainframe was also used, but to a lesser degree. Some states used portable count stations and others had permanent stations. Of the states without such equipment, many had plans to test or were already testing WIM, PIEZO electric cable, AVC, and other technologies. One state indicated the use of solar powered count and classification stations, and another was planning a project on a video counting system.

The most commonly mentioned technologies were telemetry (37% of states), WIM (28%), and AVC (26%). Uses for data from these systems included design, traffic factoring, planning, cost allocation, weight enforcement, traffic management, sufficiency studies, project scheduling, and monitoring truck trends. Some states indicated that benefits resulted from reducing the previously required manual data entry and report generation time while increasing the quality and quantity of the data.

2.3.4 Arterial Traffic Operations and Management

Only 74% of the states responded to this question, almost half of them indicating no plan to use arterial traffic control technologies, and only 42% of the states listed and described projects. However, all of the states that were pursuing arterial traffic operations and management

technologies rated these technologies as having high benefits. The majority perceived these technologies to have low cost as well.

The most commonly listed application was the use of computer programs to optimize signal timing plans for existing fixed time or traffic actuated signal systems (19% of the states), with some states pursuing state wide programs to facilitate signal optimization and synchronization. This was followed by real time signal systems that select timing plans based on vehicle detection data (16%). Some of these systems were microcomputer based systems that can be monitored and have parameters altered via remote microcomputers and phone lines. Other applications mentioned included traffic modeling/simulation, using computers for signal controller maintenance, and development and standardization of an improved microcomputer traffic signal controller.

2.3.5 Highway Information Systems and User Communications

Forty-seven percent (47%) of the states described projects in this area. However, 14% of the states listed computer communications and networking applications and 12% described highway characteristics inventories. These applications are not consistent with the definition of highway information systems and user communications mentioned previously, as outlined in the Virginia Report. Only 26% of the states listed projects that involved disseminating travel information such as traffic conditions, weather conditions,

and construction areas. Because of the large differences in the projects described, the perceived costs and benefits listed in Table 2.3 are not meaningful.

Of the states which defined highway information systems and user communications to be methods of disseminating travel information, the most widely used technology was variable message signs to warn travelers of congestion and construction areas (19% of the states). The other applications listed were radio broadcasts of travel information (12%), Advanced Driver Information Systems (7%), dial-up telephone information systems (5%), computer based road condition information systems not for general public use (5%), and television broadcasts of travel information (5%).

2.3.6 Computer Aided Planning and Design

This is the applications area which received the highest response, with 91% of the states responding and 88% listing and describing projects. It is also the area in which states perceived the highest benefits, with 90% of those responding expecting high benefits from computer aided planning and design. However, technologies in this area were also perceived to be the most costly, with 72% of the states responding experiencing high costs.

The high costs and high benefits expected are probably due to the widespread use of CADD. Many states are taking steps towards automation of the design process. Eighty-one percent (81%) of the states listed CADD projects, and most

were mainframe applications. The most frequently listed CADD applications included roadway and bridge design and drafting (74%), mapping and digitizing (21%), surveying equipment-CADD interfaces (12%), and soils and earthwork applications (12%). Other CADD technologies listed were microcomputer based CADD, generation of accident location grids, three-dimensional graphics, and photogrammetry applications. Non-CADD applications included transportation planning and network analysis applications (9% of states), automated Pavement Management Systems (PMS), automated signing plan generation, and noise barrier design.

2.3.7 Laboratory and Field Data Collection and Analysis

Eighty-six percent (86%) of the states responded in this area, and 65% listed projects. Of the states responding, 54% considered laboratory and field data collection and analysis technologies to have low cost and offer high benefits. This is the second most favorable rating in this respect, after travel monitoring and counting technologies.

A wide variety of applications were listed. Many applications listed in this category had been listed under other headings as well. For example, travel monitoring, skid resistance and pavement condition data collection from moving vehicles, survey data collectors that interface with CADD, GPS, and material testing information systems were considered to be laboratory and field data collection and analysis technologies by a few states. Projects involving these technologies were not summarized here, but discussed in other

sections, because more states placed these technologies under other headings.

Other applications listed here included computerized data collection systems that automatically record data with no need for manual data entry (14% of states), laboratory management information systems (9%), relational databases for laboratory or test data, photo/video logging, and an infrared element analyzer.

2.3.8 Construction Management and Quality Control

Almost half (48%) of the states responding (77%) in this area perceived construction management and quality control technologies to have low costs and offer high benefits. There was again wide variety in the types of applications listed and described, with 58% of the states listing projects in this area.

The most frequently listed applications were construction or project scheduling and management systems (16% of the agencies), the use of computers in construction and field offices (14%), and material testing information systems for storage, retrieval, analysis, and reporting of test results (14%).

Other applications listed included personnel and manpower management systems (9%), bid and contract analysis and management systems (9%), automation of progress payments to contractors (5%), funds management, inspection information management, and field data collection with computers.

2.3.9 Advanced Survey and Positioning Systems

Most of the states answering this question indicated the use or investigation of Global Positioning System (GPS) applications. Forty percent (40%) of the agencies indicated some degree of involvement with these technologies. Of the 81% responding, 57% perceived advanced survey and positioning systems to offer high benefits, and 40% perceived low costs as well. Items listed included electronic Theodolites, AASHTO's Survey Data Management System (SDMS), GIS applications of GPS, airborne kinematic GPS for photogrammetric purposes, and the use of GPS for highway characteristics inventory data collection.

2.3.10 Other

This category was provided to encompass applications that did not fit into the other categories provided. Only 16% of the states listed projects in this category. Applications listed included word processing, spreadsheets, automated generation of straight line diagrams, computerized engineering copiers, computerized postage scales, weather and pavement surface sensing systems, executive information systems (EIS), and an accident reduction program involving computerized mapping and traffic and road characteristics databases.

Table 2.4: Possible Barriers to Advanced Technologies

| Barrier: | Percent of States Responding |
|--|---------------------------------|
| High Initial Cost | 79% |
| Lack of Trained Personnel | 74% |
| High Operation and Maintenance Cost | 56% |
| General Resistance Against Change | 53% |
| Uncertainty About Potential Benefits | 51% |
| Uncertainty About the Type of Technologies That Can Be Used | 35% |
| Poor Training and Support Offered By Vendors | 21% |
| If You Wait, Even More Advanced Systems Will Be Available Next Year | 19% |
| Fear of Labor Displacement | 12% |
| Lack of Provisions in Contract Agreements | 9% |
| Unable to Get Funding | 2% |
| Liability Regarding IVHS and Anti-Trust | 2% |
| Managers Overburdened by Rate of Change | 2% |
| Space Shortage for Computer Systems | 2% |
| Necessary to Custom Design and Build with Much Systems Integration Work | 2% |
| No Assigned Development Group | 2% |

2.4 Barriers Against the Use of Advanced Technologies

Agencies were also asked to check possible barriers to the use of computer and advanced technologies. Several states listed other barriers that were not included on the original questionnaire. All responses are summarized in Table 2.4.

2.5 Other Areas With High Potential

Finally, agencies were asked to list other areas they felt had high potential for application of advanced technologies. Over fifty ideas were listed, with very few being repeated. Most of the items listed were areas in which other states had listed projects elsewhere in the report. For

example, some areas listed included GIS, EIS, imaging technology and expert systems.

Items that were not covered earlier in the chapter included contractor qualifying, hazardous materials emergency response, voice mail, automated measurement of sign and pavement marking reflectivity, training, large bridge monitoring with GPS, electronic storage of as-built plans, optical disk storage, and videotext for telebanking, teleshipping, and in support of transit/rideshare activities.

2.6 Status of Advanced Technologies in Transportation - 1985

In 1985, the Virginia Department of Highways and Transportation (Hoel 1985) investigated the use of advanced technologies in transportation agencies. The investigation included a survey on the use of advanced technologies that was sent to all fifty states, from which forty-six states responded. The states were also asked to describe research and development (R&D) projects underway at the time, describe any collaboration with universities or the private sector, and indicate areas in which computer technology was being used. Findings on R&D projects are summarized in Table 2.5, which shows not only the percent of the states that reported current projects, but also the total number of projects in each area.

Areas in which computer technology was being used are summarized in Table 2.6. This table shows the percentage of states that were using different computer technologies at the time, as well as those areas that state officials believed had

high potential for future application.

Table 2.5: Research and Development Projects, 1985 (Hoel)

| Area | Percent of States With Projects | Number of Projects |
|--|---------------------------------------|-----------------------|
| Computerized Design, Analysis and Planning | 57% | 36 |
| Database Management and Information Systems | 46% | 30 |
| Highway Traffic Operations and Management | 43% | 39 |
| Laboratory and Field Data Collection and Analysis | 33% | 25 |
| Construction Management and Quality Control | 15% | -- |
| Highway Information Systems and User Communications | 11% | 6 |

Comparing the results of the two surveys indicates growth in the use of advanced technologies during recent years. Except for highway information systems and user communications, the results of Table 2.6 indicate that the use of advanced technologies in the listed areas has either grown or stayed high. Furthermore, most states in the 1989 survey misunderstood the definition of highway information systems and user communications, and this may be the reason for the difference in results in this area.

Table 2.6: Use of Computer Technology in State DOTs - 1985

| Area | Percent of States Using High Technology | High Potential Application |
|---|---|-------------------------------|
| Database Management | 87% | 48% |
| Computerized Design, Analysis and Planning | 83% | 76% |
| Laboratory and Field Data Collection and Analysis | 72% | 30% |
| Highway Information Systems and User Communications | 67% | 39% |
| Automated Sampling and Quality Control | 20% | 4% |
| Artificial Intelligence | 0% | 2% |
| Other (Shown Below) | | |
| Office Automation (Florida) | | |
| Environmental Protection Modeling (Hawaii) | | |
| Analytical Models (e.g. HPMS, HIAP, etc.) (Idaho) | | |
| Nondestructive Testing of Bridges and Pavements (Minnesota) | | |
| Surveying Data Handling (Minnesota) | | |
| Communications and Real Time Traffic Control (Texas) | | |
| Traffic Management Systems (Virginia) | | |
| Signal Timing Plans (Virginia) | | |

The "Other" applications areas in Table 2.6, where only one or two states used advanced technologies in 1985, are the areas that grew the most. Now several states have or are pursuing technologies in these areas. Other areas that experienced very high growth were construction management and quality control and expert systems. The use of advanced technologies in the remaining areas was high then, and remains high now.

2.7 Summary

The results of the survey indicate that many states are actively pursuing R&D projects involving advanced technologies. The most pursued technologies at present are GIS and numerous computer applications. Computer applications range from mainframe-based CADD systems to small microcomputer applications. At least two-thirds of the states have R&D projects in these areas. This does not count states that already have working systems and are not currently involved in R&D.

The most highly pursued computer applications are listed in Table 2.2. Most of the R&D projects involving computer applications listed in this table were also frequently listed in the applications section of the survey. Therefore the percentages listed are significantly lower than the actual number of states with some kind of activity in each area.

Real time traffic control, IVHS, and expert systems are also being actively pursued, although to a lesser degree. Approximately one quarter of the states have current R&D projects in each of these areas.

Most automatic vision and image processing R&D projects dealt with video image processing for traffic surveillance and data collection. This is an area that can greatly effect further developments in real time traffic control and IVHS. Real time traffic control projects primarily concerned FTMS, with many states already having working FTMS systems. Arterial traffic management applications were also mentioned.

A variety of IVHS projects were listed covering all technologies that are generally placed under the IVHS heading. Many urban areas have already been successful in applying some of the user communications portions of IVHS, mostly in conjunction with FTMS. A wide variety of expert systems were mentioned, with 13 projects listed and described. Some were working systems, while others are still under development.

Robotics in construction and maintenance was the area where the fewest states (only 9%) had R&D projects. This is the least actively pursued area, probably partially due to the extreme and varied conditions robots must face in the field as opposed to the controlled environments available in manufacturing applications.

Apart from R&D projects, many states have successfully applied many new technologies. The perceived costs and benefits associated with these technologies and the number of states using or planning to use them, can be used to judge their effectiveness.

The most widely used technologies are database management, computer aided planning and design, and travel monitoring and counting technologies. Less than 10% of the respondents had no plan to apply these technologies.

All the states using database technology considered this technology to have high benefits, although states were divided on whether the costs were low or high. This is most likely due to differing levels of involvement. The database applications most commonly listed were relational/integrated

databases and/or GIS, computer inventories, pavement and bridge management databases, project/program management databases, financial management systems, and overall MIS or database restructuring projects.

Computer aided planning and design received the highest response rate, and the highest percentage states perceiving the technologies to have high benefit (90%) as well as high cost (72%). This is due to the widespread use of CADD, with 81% of all agencies reporting CADD projects for a variety of applications.

Travel monitoring and counting technologies were also very widely used, and had the highest number of states perceiving low cost and high benefit associated with their use. The project descriptions listed indicated widespread use of automated counting systems involving various combinations of telemetry, AVC, WIM, speed sensing, and other technologies.

Laboratory and field data collection and analysis, construction management and quality control, and advanced survey and positioning systems were the next most widely used technologies. Between 19% and 26% of the states had no plans to use these technologies. The majority of the states that had developed applications in each of these areas perceived them to have low costs and high benefits.

There was a wide variation in the types of projects listed under laboratory and field data collection and analysis and construction management and quality control. There was

also some overlap between the two categories, with laboratory and material testing information systems and computers for automated field data collection listed under both categories. There was some overlap between these categories and other categories such as travel monitoring and counting as well.

Other projects frequently listed in the two categories included relational databases in the lab, photo/video logging, construction or project scheduling and management systems, the use of computers in construction and field offices, personnel and manpower management systems, bid and contract analysis and management systems, automation of progress payments to contractors, financial management systems, and inspection data management systems. Most of the items listed under advanced survey and positioning systems dealt with applications and planned uses of GPS.

The least pursued applications area were arterial traffic operations and management, and automated pavement and bridge distress sensing systems. Over 40% of the states had no plan to use technologies in these areas. However, this can be misleading, especially in the arterial traffic operations and management area.

All of the states actually using arterial traffic operations and management technologies perceived these technologies as yielding high benefits, and the majority of these states perceived low costs as well. The most frequently listed applications were the use of computer programs to optimize signal timing plans and facilitate signal

synchronization, real time traffic control based on vehicle detection data, and traffic modeling/simulation.

Almost all of the projects listed under automated pavement and bridge distress sensing systems dealt with using vehicles equipped with computers to collect data for various combinations of pavement rutting, roughness, geometry, skid resistance, and deflection basins. Very few bridge applications were mentioned. Of the states using technologies in this area, 47% perceived high cost and high benefit, and 26% perceived low cost and high benefit.

The ratings for the last applications area, highway information systems and user communications, were not very meaningful because the projects listed indicated that most states did not understand the definition intended by the survey. Many states described computer networking, computer communication systems, or highway characteristic inventory applications. Only 26% of the states listed projects that involved disseminating travel information to travelers.

CHAPTER 3: COMPUTER AIDED DRAFTING AND DESIGN

Computer Aided Drafting and Design (CADD) refers to interactive computer graphics software developed for design and drafting use by architects and engineers. Many different companies and agencies have developed CADD software for use on microcomputers, mini-computers, and mainframes. A variety of engineering applications have been incorporated into these software packages.

CADD can be used to create planar drawings and three-dimensional models, which are stored in data files. These data files generally can not be transferred directly from one type of CADD software to another; however, programs do exist for translating data between different CADD systems. It is possible to attach various spreadsheets or databases to a CADD drawing, so that a specific coordinate in the drawing can be connected to information within a database. In some CADD systems, data is managed with separate software, and in others, the CADD system contains it's own programming language. In planar drawings, it is possible to add various layers to a drawing, and call up only the desired layers for display.

A recent publication of the Transportation Research Board (TRB) (1990) provides a detailed description of CADD and

discusses key issues in the successful development of CADD systems within local and state transportation agencies. The five major components of a CADD system are:

- *The Central Processing Unit (CPU) - A mainframe, mini, or personal computer. It executes commands, reads and writes data files, performs calculations, processes data, and translates data files into images.
- *Input Devices - Keyboards, command menu tablets, digitizing tables, scanners, stereo plotters, and survey data collectors.
- *Output Devices - Videoscreens, plotters, and printers.
- *Data-Storage Devices - Hard disks, floppy diskettes, and tape.
- *Software - Operating system and applications software.

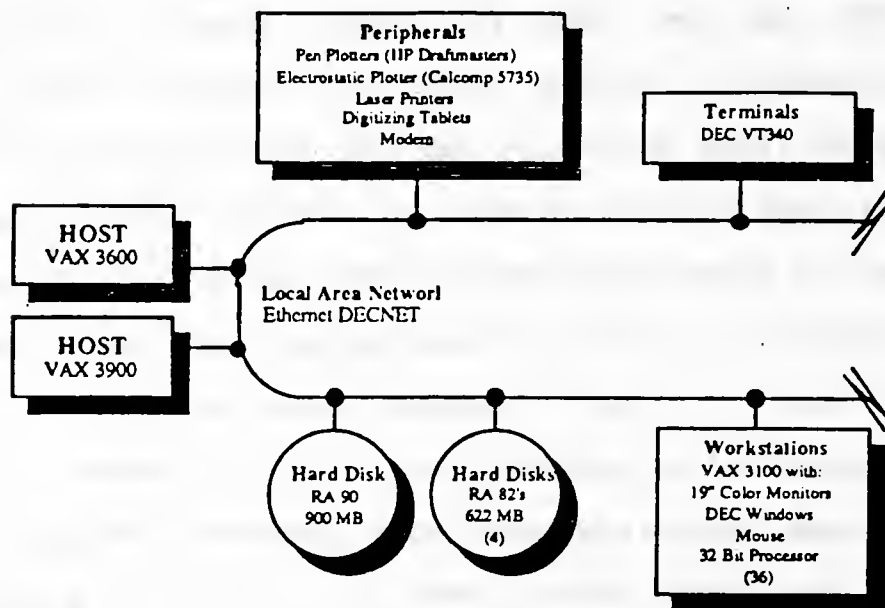


Figure 3.1: Components of INDOT's CADD System
(Source: Vanegas 1990)

Figure 3.1 illustrates a typical mainframe based CADD system, as it exists in INDOT. Most of the states use Intergraph software. Other equipment and software used includes Hewlett Packard, McDonnell Douglass, Tektronics,

Diginetics, Autotrol, IBM, AutoCADD, and AASHTO's IGrds. Crawford and Chavez (1990) discuss the use of IGrds in Texas.

Computer and CADD hardware and software continually develop and become outdated. Vendors and suppliers continually make new product announcements. The TRB report (1990) acknowledged that trying to discuss the latest hardware and software is futile due to rapid technological advances, and recommended subscribing to industry newsletters and periodicals, and attending association and users' group conferences, in order to stay up-to-date on the state-of-the-art. Instead of discussing the latest technology, the present study concentrated on applications and management issues.

Vanegas (1990) investigated the current status of CADD within INDOT and developed several preliminary recommendations to aid in the management of INDOT's CADD program. His findings were updated to take into account recent developments, and additional research was done to identify some of the key requirements for successful CADD programs. The results are summarized below. Included are a list of CADD applications, a discussion of general requirements for a successful CADD program, a description of the current status of INDOT's CADD system, a discussion of the costs and benefits of CADD, and recommendations for INDOT's CADD system.

3.1 Applications

A wide variety of very specific applications are available for mini-computer and mainframe based systems. The

availability of a wide variety of applications for specific disciplines on microcomputers has lagged behind larger systems, but is rapidly catching up. The TRB report (1990) broke down CADD applications in state transportation agencies into five basic categories:

- *Roadway Design and Drafting
- *Bridge Design and Drafting
- *Interactive Photogrammetry
- *Automated Survey Data Collection
- *Mapping

Nearly the entire roadway design and drafting process can be done using CADD, including horizontal and vertical alignment, plot and profiles, earthwork estimation, and design of many special structures, to name a few. Bridge design and drafting has developed slightly less rapidly. Two commonly used softwares are AASHTO's BRADD-2 (Bridge Automated Design and Drafting System) and BDS (Bridge Design System), which can run on a variety of equipment. BRADD-2 allows almost entire automation of the design and drafting process, but can be used only on simple structures. It reduces the time for complete design of a simple bridge to 120 man-hours. BDS performs a variety of functions for more complex structures, but the degree of automation is considerably less.

It is now possible to link CADD systems to photogrammetric equipment so that maps can be drawn directly into the CADD database. This is referred to as Interactive photogrammetry. Automatic survey data collectors can be

linked to survey equipment, and automatically input survey data into CADD format. CADD can also perform many mapping functions.

In addition to the above applications, many more complex developments may occur in the near future. For example, when CADD becomes standardized on construction projects, it may be feasible to control equipment such as graders, track building materials, track progress, and provide continuous information on the design to layout crews, using advanced positioning systems integrated with CADD on the construction site (Beliveau 1989). CADD may also be merged with expert systems to automate design. Many states are moving towards increased automation of the design process.

Furthermore, as CADD use increases, the availability of predigitized base topological and environmental map data is also increasing. This allows for less expensive development of base CADD maps. Vitale and Galbraith (1990) discussed sources of this data and described how it can be used in corridor and EIS studies.

According to the TRB study (1990), 14 design applications and 13 planning and mapping applications were used in the state DOTs in 1988. These applications were:

- * Roadway Drafting,
- * Bridge Drafting,
- * Generating Cross Sections,
- * Traffic Analysis,
- * Architectural Design,
- * Bridge Design,
- * Digital Terrain Modeling,
- * Earthwork Analysis,
- * Survey Data Reduction,
- * Coordinate Geometry,

- * Horizontal Roadway Alignment,
- * Soils Log Drafting,
- * County Maps,
- * State Highway Maps,
- * Urban Highway Maps,
- * Photogrammetric Mapping,
- * Special Maps,
- * Traffic Analysis Maps,
- * District Highway Maps,
- * GIS Maps,
- * Cartography,
- * Planning Maps,
- * Airport Utility Maps,
- * Land-Use Maps, and
- * Wetland Maps.

The most cost effective design applications were roadway design, bridge design, interactive photogrammetric mapping, quantity takeoffs and estimate sheets, automated survey data collection, right-of-way plan drafting, typical sections plan drafting, traffic sign design, architectural drafting, boring logs drafting, county highway mapping, earthwork analysis, and generating profiles.

3.2 Requirements of a CADD Program

The amount of resources that can be tied up in a CADD system and the enormous impact that CADD can have throughout an organization require careful and methodical development. A panel discussion at the 1990 ASCE Professional Development Seminar held at Purdue University focused on the issue of how to manage a CADD system. The TRB report (1990) and McGinnis and Wagner (1989) outlined basic methodologies for developing and managing CADD systems. The information obtained from these sources was combined with the initial findings of the present study (Vanegas 1990) to identify four key components

of successful CADD systems. The issues identified were commitment, planning, management, and training. This discussion does not analyze every detail of a CADD system, but provides a general outline and highlights some important issues.

3.2.1 Resource Commitment

Once a decision has been made to take advantage of CADD technology, it is necessary for top level management to commit resources to system development immediately. Selecting hardware and software, dealing with vendors, and identifying system requirements require many man-hours of work. Also, as with any new technology, resistance to change and organizational problems may be encountered at various levels of the agency. It is important that high level management be prepared to deal with these problems.

One important aspect of commitment is selecting a system manager who can put in the necessary man-hours. It is important that this person is enthusiastic and has experience with the technology in order to identify potential applications. It is preferable that the person is familiar with agency organization as well.

A Michigan DOT official, in an interview with the study team, discussed the successful implementation of the CADD in Michigan DOT and the importance of selecting a "champion" to represent and advance a new technology. This champion can be a single person or a task force. The champion must be

reliable, capable, experienced, resourceful, motivated, and needs to be given the authority and upper level management support to overcome resistance. Resistance may come from budgeting, fellow employees, other staff members, and possibly even upper level management.

3.2.2 Planning

Another key issue is planning. Careful and well documented planning must begin even before hardware and software are selected. Hardware and software can not be selected without first identifying the system requirements. Identification of system requirements, in turn, depends on accurately defining system and departmental goals, system user requirements (needs), and existing resources and constraints (facts).

After goals, needs, and facts have been clearly defined, specific strategies for fulfilling the goals and needs while staying within the constraints (concepts) can be developed. Developing and pursuing these concepts forms the essence of the planning process. In addition, it is desirable to identify and address specific concerns or areas of interest (issues) as they arise. This will help maintain focus and insure continuity for the planning process. Thus the planning process consists of goals, needs, facts, concepts, and issues.

Defining the goals and needs depends on answering the question: "What do we want the system to do?" This is an important question, and answering it requires identification

of all desired applications. Thus, a good place to start the planning process is to look at specific CADD applications. Commonly used applications include roadway design, bridge design, earthwork estimation, hydraulics design, traffic design, and structural design. Currently the majority of the time spent using CADD among the state agencies is for drafting. Possible future GIS applications should also be taken into account, since CADD technology is one of the building blocks of GIS.

One useful tool for identifying applications is to look at what other agencies and states are doing. It may be desirable to conduct detailed interviews with a few select experts from outside of the agency, such as personnel from other state DOTs that have already developed successful systems, or FHWA representatives.

Another method of identifying desired applications, and thus defining goals and needs, is to conduct intra-departmental interviews with personnel from various divisions and sections that would be affected by the technology. In fact, when used properly, intra-departmental interviews can serve many functions.

In the early stages of investigation of a new technology, department personnel may not be very familiar with the technology. The interview can be used to familiarize interviewees with the new technology, thus paving the way for future implementation and initiating communication about the technology.

Interviews can also be used to help quantify potential benefits. This may be an important step in justification of the expenditures necessary for a successful program. However, quantifying benefits can be difficult with new technologies because the future users have no experience with the technology and there are possible future applications that may be difficult to foresee. It may not be possible to quantify all benefits, but asking interviewees to estimate the benefits (time savings, etc.) that would result from specific applications is a good starting point.

In lieu of interviews, other data collection techniques such as questionnaires and surveys could be used. These methods would likely be less costly in terms of man-hours, but the quality of information exchanged would probably not be as high.

Identification of existing resources and constraints, or facts, should occur concurrently with the definition of goals and needs. These facts may include hardware inventories, software inventories, capabilities and limitations of existing system components, space constraints, budget constraints, time constraints, defining current processes, identifying current costs, and human resources.

Facts must be identified before selecting hardware and software. It is important to define the existing data processing environment, in order to evaluate the software under consideration. The software language, availability of source or object code, memory requirements, and vendor

installation support, including debugging and vendor customization, may all be important issues, depending on the existing facts.

Once goals, needs, and facts have been identified, specific planning strategies (concepts) can be developed. Such information is vital to the planning process, and it should be consolidated into a formal master plan. A CADD system constantly faces challenges. Facts, needs, and goals change with time, which necessitates revision of the concepts. Consolidating important information into a single source, the master plan, allows for continuity, reduction in duplicated effort, and more efficient planning.

The master plan should address all vital issues, including hardware configuration, software applications, economic investment, and an implementation schedule. The implementation schedule needs to include support staff training; hardware delivery, installation, testing, and acceptance; software delivery, installation, testing, and acceptance; user training; user familiarization; and production use. It is important to keep the implementation schedule up to date as changes are encountered. The plan should also identify milestones, where senior management can evaluate and approve progress before continuing.

There are several special issues that may need to be resolved before the above mentioned vital issues can be fully addressed. Special issues may include hardware/software selection, pilot studies/demonstration projects, networking,

agency/design consultant interface, survey interface, development of a management structure, and training methodologies. Management and training are larger issues, and are discussed in separate sections later in the chapter. The other special issues are discussed in the following paragraphs.

Hardware/Software Selection

The goals and needs gained from interviews, along with facts, can be used to develop system requirements for hardware/software selection. For example, looking at the desired applications will define the various types of output the system must be able to generate. These requirements can serve as the basis for a request for information, which could be used to obtain information from various vendors concerning their ability to meet agency requirements.

When considering equipment, it is important to consider total cost, not just initial cost. Total cost includes hardware costs, software costs, delivery and installation, staff training, support staff training, system maintenance, establishing CADD standards, space renovation, air conditioning, power conditioning, the cost of converting standard details and drawings to a CADD standards library, the vendors maintenance contract, supplies, development costs, customization, software updates, management, reorganization, and other administrative costs.

It also may be beneficial to consider using less powerful

micro and PC based workstations that are adequate for some applications, although they can not perform all the functions of complete workstations. These stations may have a high performance/cost level, and may be used as stand alone systems or networked into a larger mainframe based system.

Vendor services such as training, support, installation, debugging, software upgrades, system maintenance, and availability should also be taken into consideration. In general, more services will cost more. Each vendor must be evaluated for technical expertise and reliability. It is also helpful to require vendors to conduct benchmark performance tests and demonstrations before purchase.

Pilot Studies/Demonstration Projects

Small scale projects in which only a few applications are developed can be a very important step in implementation. Demonstration projects allow for major bugs to be worked out before attempting to adopt a system on a wide scale, and for more smooth merging into existing operations. Furthermore, the staff trained in a demonstration project can assist in training other personnel during subsequent implementation phases.

Networking

Both local area and wide area networks (LAN and WAN) need special consideration to insure efficient sharing and communication of data, and to avoid duplication of data.

Networking lower cost PC based workstations into the system should also be considered, possibly through use of a demonstration project.

Agency/Design Consultant CADD Interface

Developing standards for digital data interface between the agency and design consultants allows consultants to submit designs in an electronic format that is compatible with or easily accessible by the agency's system, and allows the agency to give data to consultants in the same manner. Consultants use CADD extensively, and allowing submittal in electronic format could decrease the work load, and thus lower costs, for both parties. This will also allow data to be shared with other agencies. Figure 3.2 illustrates the information exchange process for road design and graphics.

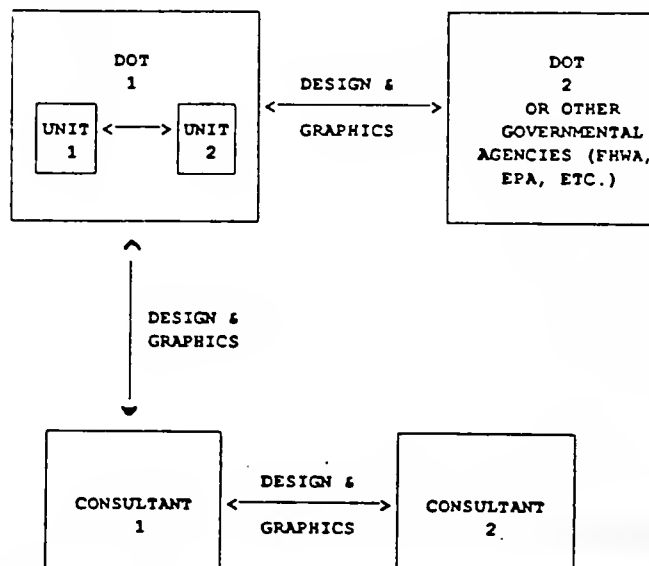


Figure 3.2: CADD Data Transfer Needs
(Source: NCHRP Report 326)

When the CADD systems of sharing parties are not the same, the DOT can require consultants use a particular format,

or neutral formats can be established. Neutral formats supported by various vendors and agencies include Intergraph Standard Interchange Format (ISIF) from the Intergraph Corporation, AutoCADD Drawing Exchange Format (DXF) from Autodesk, Inc., Initial Graphics Exchange Specifications (IGES) from the National Bureau of Standards, and the United States Geological Survey (USGS) Digital Line Graph (DLG) format. In addition, AASHTO and the FHWA, as described in NCHRP Report 326, are developing the Common Data Interchange Format (CDIF).

Most of the states that have specified a neutral format are using ISIF. The most widely used format among state DOTs is Intergraph's IGDS, and the Florida DOT has recently required that consultants prove they can freely translate between IGDS and their own formats. Most states have not yet specified standard or neutral formats, but work with consultants individually, accepting some hard copy and some electronic data.

Survey Interface

Many agencies use automated survey data collectors or photogrammetric interfaces that allow survey data to automatically be transferred into CADD format with minimal effort. Such applications should be considered early in the design process, so that coordination with surveys can be obtained. CADD is driven by survey data, and entering these data manually or through scanning is too time consuming.

3.2.3 Management

Management is a very important issue. A CADD system will continually face challenges, and even change the department's daily operations. Even when CADD has been implemented state-wide, continuing reassessment is needed to maintain the effectiveness of the design system. A suitable management structure needs to be developed in the master plan to deal with these challenges. This management structure may need to be changed as the agency gains experience with the system, or as new applications are added. Issues that management may need to address include implementation and interface issues, system assessments, training, data management, and ergonomics/personnel management.

Implementation and Interface Issues

As CADD is implemented, difficulties will be encountered. Personnel will need to be reassigned and retrained. Different functional areas of the department will encounter their own special problems. Each area needs individual assessment, but special attention also needs to be paid to interface and coordination between the different areas.

System Assessment

Continuous assessment is required to make best use of the committed resources. This includes analyzing both how the users can better use the system, and how the system can be altered to better support the operations, or users. Changes

in design procedures and criteria will require revisions throughout the department. Hardware, software, training, and management will all be affected. Furthermore, a procedure needs to be developed to evaluate new applications as they become available, and recommend their implementation.

Data Management

Many data management issues will arise with use of CADD. The quality and accuracy of CADD applications depends on the quality and source of the data. Users must understand the accuracies and sources of the data they are using. Backing up data is also important. The procedures and frequencies for backing up data need to be addressed. Guidelines need to be in place as to how long to keep data in the computer after a job has been completed. Archiving may also be an issue. It may be wise to save data for long term in hard copy, as disks can fail or even become obsolete as improved storage methods become available. Guidelines for sharing data between users are necessary as well, so that the personnel working on a given project are not working with obsolete data files that have been altered elsewhere by another user.

Ergonomics/Personnel Management

Sitting at the computer day after day may become tiresome for even dedicated users, causing interest and productivity to fall. Training a person on CADD is a considerable investment, and attention needs to be paid to ergonomics to insure that employees do not want to jump ship after they have been

trained.

Management tools for keeping interest high include conducting periodic job evaluations, creating new job titles, providing incentives, allowing for job advancement in the new organizational structure, and moving workstations out into general work areas after training is completed.

Proficient CADD users are in high demand throughout the engineering profession. It may be necessary to raise pay to keep trainees from leaving the agency. The agency may also need to develop more than one shift to maximize the use of the equipment. In this case, extra compensation will be needed.

3.2.4 Training

Training, like management, is an issue that should be considered early in the planning process. The amount and type of training supplied by vendors differs, as does the amount of training required by users. Thus it is necessary to consider training even before hardware and software are selected.

Defining needs should give an indication of the amount of training required, but each vendor needs to be analyzed individually. Before software is purchased, it is necessary to determine (1) if software purchase includes initial user training, (2) if this training is adequate, (3) the cost and availability of additional training, (4) who provides the training (vendor or subcontractor), (5) if on-site training is available, (6) if training can be customized, (7) length of training, (8) if follow-up training is required and/or

available, (9) trainee prerequisites, (10) the availability and type of course materials, and (11) if updates are included in the package. These points apply to both user and support staff training.

Apart from vendor training, the agency may wish/need to take over part of the training process. If this is the case, then a training system must be developed. Gier and Nelson (1989) outlined some of the essentials of a CADD training course. They discussed five key points: developing goals and objectives; course organization; teaching style; course evaluation and feedback; and development, revisions, updates, and bugfixes. The most important thing to remember, however, is that the training must be evaluated periodically. Revisions will need to be made based on trainee feedback, teaching experience, vendor updates, and the availability of alternative and more modern materials, courses, and delivery systems. Therefore the master plan should develop a system for evaluating and managing the training process.

In addition, the panel discussion held at Purdue on CADD suggested several guidelines for CADD training. Some of the guidelines used by a local consultant follow:

- When selecting CADD trainees, ask for volunteers and pick the best people. This is not the place for staff that have not been successful elsewhere. Also, look for computer literacy, and pick staff with experience in the discipline. It is much easier to learn just CADD than to learn CADD and highway design at the same time. Only enough people should be accepted in the training program as are needed in the short term, and volunteers must understand that acceptance may mean some adjustment in working hours.

- Instructors must have practical experience in the discipline,

as well as being familiar with the CADD system. Initially a ratio of one instructor per every three trainees should be used.

- Train 2 to 3 operators per screen and allow enough time for classroom and screen time instruction. All trainees should be committed to at least 6 to 10 weeks of training and practice.
- Drafting techniques should be taught before design techniques, and plotting practice should be included.

3.2.5 Summary of Important Issues

The TRB report (1990) provided a checklist of some of the key issues to be addressed in the planning and implementation process. Most of these issues were discussed previously. In summary, they include:

- 1) Obtain committed support from high level management
- 2) Conduct a thorough requirements analysis
- 3) Employ a systematic selection process to evaluate all vendors
- 4) Develop a comprehensive implementation plan
- 5) Identify all purchase costs
- 6) Identify all operating costs
- 7) Establish an ongoing user support and training program
- 8) Carefully identify, examine, and plan all applications for the system before purchase
- 9) Set productivity improvement and system assessment guidelines
- 10) Set data standards
- 11) Establish personnel policies for CADD users, including:
 - Personnel selection
 - Performance evaluation
 - Compensation
 - Shift pay
 - Promotion
 - Discipline and experience of trainees

CADD is a widely used technology. There are many people that have dealt with the issues discussed in this chapter. It is important to remember that others may be more than willing to discuss their experiences with CADD. Professional conventions and seminars present an excellent opportunity to talk with others to gain insight into which systems have been successful, and how other agencies have dealt with similar problems.

3.3 The Status of CADD in INDOT

The use of CADD in INDOT was summarized in an earlier working paper (Vanegas 1990). Additional interviews were conducted to update the initial findings. The INDOT has been continually expanding its CADD use and many developments have occurred since the earlier report, but the earlier findings are still predominantly true. Therefore, the findings are not discussed again in detail in this section, but merely touched upon and updated where necessary. For more detail on the hardware, software, and implementation plan, the working paper can be consulted.

INDOT has made significant progress in the use of CADD. Originally, a five phase implementation plan was devised with phase I, initial implementation, being completed in 1989. Phase I included installation of:

- *A central processor (Micro VAX 3900).

- *Nine intelligent workstations (DEC VAXstation 3100) with 32 bit processors, 19" color monitors, DEC windows, and mouse.

- *Terminals (DEC VT340).

*An Ethernet Local Area Network DECNET.

*Peripherals (digitizers, printers, and plotters)

In addition, the system has two VAX 3900 hosts, one RA 90 900MB hard disk, four RA 82 622MB hard disks, and a HASP Civil Engineering Stereo Plotter. HASP can connect between different CADD formats, and allows INDOT to interface their system with Autocadd, DLG, and other formats.

After successful testing during phase I, the implementation schedule was accelerated and revised into a four phase plan (Figure 3.3). Currently INDOT is nearing completion of the accelerated phase II. All phase II equipment has been installed, giving a total of 37 networked workstations, and phase II training has been completed. All that is needed to test a remotely networked workstation is fiber optic cable, which is in the procurement process. At this point, equipment alone has cost approximately \$50,000 per seat.

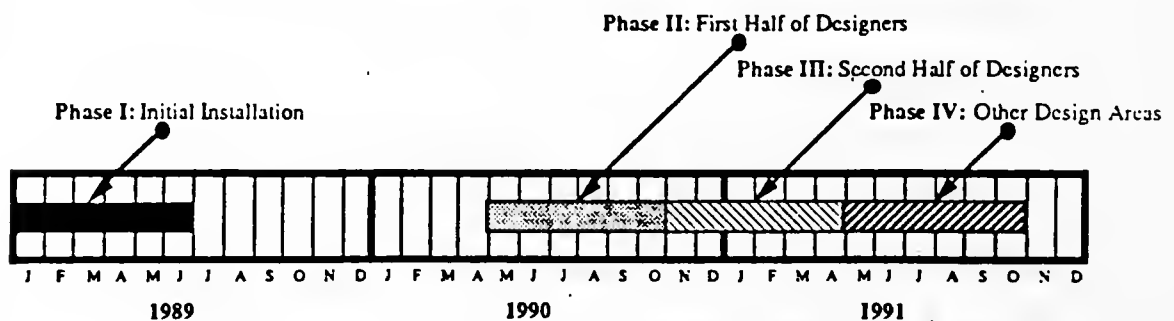


Figure 3.3: INDOT's Accelerated Implementation Plan

The INDOT CADD system is based on three engineering programs, but only two of these programs are currently used.

The three programs are:

- *Graphics Design System (GDS) for drawing work,
- *Coordinate Geometry (COGO)/Roadway Analysis and Design System (ROADS) for solving geometric problems and automating the roadway design process,
- *Modeling of Surface Strings (MOSS) for three dimensional modeling of topographical data.

There is no need for COGO ROADS because GDS has COGO capabilities and MOSS is used for design. It is easy to move back and forth between MOSS and GDS. INDOT is considering purchasing another CLM software. CLM software has been standardized in sixteen DOTs and can run on a PC on DOS.

The recently created Engineering Graphics Section within INDOT manages the CADD system. The section provides high level support by assisting in the evaluation, recommendation, selection, training, implementation, and maintenance of CADD hardware and software.

Training takes six weeks at eight hours per day, and involves manuals, instruction, problem sets, and skills development time. Initially training was done by McDonnell Douglas, but now GDS training is done in house. MOSS training is still purchased from McDonnell Douglas.

All road and bridge design is now done on CADD, including development of plans and drawings. This allows many options to be tried quickly. Future applications envisioned include GIS, Engineering Services (cartography and contracts), Program Development (preliminary engineering studies), Land Acquisition, District Offices, Construction, and further use in Design (survey, photogrammetry, plan development, traffic

engineering, hydrology, utilities, and railroads). Interest has also been expressed in developing an INDOT/design consultant CADD interface.

INDOT considers GIS to be an application of CADD and has taken steps in acquiring GIS capabilities. This is discussed in the following section on GIS. INDOT has also successfully used electronic data collection to collect survey data for design. Survey data are collected on a computer using a Lietz SDR24 data collector that interfaces with a TOPCON electronic total station. It must be plugged into the mainframe later to upload data for CADD, but INDOT plans to acquire laptops to eliminate this step. Electronic data collection is now used on all projects.

3.4 Costs and Benefits of CADD

The state agency survey conducted in the study indicated that CADD is presently one of the widely used as well as most costly advanced technologies. The hardware/software purchases, system management, department reorganization, planning, and training required for a successful CADD program involve the commitment of large amounts of resources, for mainframe based systems. However, the survey also indicated that agencies which focus on PC-based systems consider the costs of CADD technology to be low, and that the high costs of CADD systems are more than offset by the high benefits resulting from the use of CADD.

The benefits of using CADD are basically related to

productivity improvements. Some benefits are easy to quantify and others are not. Benefits include time savings, better drawing quality, increased standardization, greater ease in making drafting changes, and the ability to quickly try alternative designs.

Costs include purchase, implementation, maintenance, and development costs. A recent TRB study found that equipment costs have decreased an average of ten percent per year between 1982 and 1988 (NCHRP Synthesis 161).

During this period the cost of an installed minicomputer system fell from \$109,000 to \$60,000 per workstation, including taxes, insurance, delivery, and installation charges. PC-based systems fell to under \$15,000 per workstation. This fall in price was accompanied by a large increase in capabilities.

The NCHRP Synthesis also suggested that CADD applications must result in a 2:1 increase in productivity over manual methods to offset the additional system costs. In addition, they found that the average productivity for all applications areas in 1988 was 3.6:1, and suggest evaluating productivity in terms of labor savings.

This can be done by amortizing system purchase and installation costs and adding yearly operating costs to calculate total annual system costs. Dividing annual system costs by the total yearly hours of production use gives the hourly system cost per workstation. Comparing the hourly cost of using CADD for a given application with the hourly costs of

previous methods indicates the time savings needed to justify CADD for that application. An analysis period of 3 to 5 years is recommended. This does not take into account other benefits of CADD that are not easily quantified.

For example, INDOT began implementing the CADD system in January 1989, and acquired 53 workstations for approximately \$4 million, or \$75,500 per workstation. This includes installation, consulting fees, hardware, software, and licensing fees. Ten of these workstations are for GIS use only.

The system's maintenance, management, and training costs are not readily available from INDOT. NCHRP Synthesis 161 outlines some assumptions for estimating these costs. The assumptions are as follows:

- Each terminal is actively used 25 to 30 hours per week per shift (5 to 6 hours/day). Using the smaller figure will account for training, development, and other indirect uses.
- Annual maintenance is 10% of the purchase and installation cost.
- Eight full time personnel are required for system management and operations support with average salaries of \$25,000 per year. Employee benefits amount to approximately 50% of salaries.
- Supplies and utilities cost \$1,500 per year per workstation.
- Two workstations of each 20 are used for training, system support, and research and development, thus they are not in direct production use.
- There are 237 days available for operation per year, after taking annual leave, sick leave, and holidays into account.

If the system is used for one shift per day and an analysis is done over a period of 5 years, the hourly cost per

workstation of the CADD system can be estimated as follows:

43 workstations X \$75,472/workstation = \$3,245,300 purchase and installation costs

50 personnel X 6 weeks X \$15/hr = \$180,000 training costs

\$3,245,300 + \$180,000 / 5 years = \$685,060 annual depreciation costs

\$3,245,300 X 0.1 = \$324,530 annual maintenance costs

8 personnel X \$25,000 per year = \$200,000 annual salaries

\$200,000 X 0.5 = \$100,000 annual employee benefits

43 workstations X \$1,500 = \$64,500 annual supply and utility costs

Total annual costs = \$1,374,100

39 production workstations X 5 hours/day X 237 days/year = 46,215 hours/year of production use.

\$ 1,374,100 / 46,215 = \$29.75/hour per workstation cost of production use excluding operator salaries. If the system were run on two shifts this cost would be nearly halved.

The hourly cost of CADD can be used to evaluate specific CADD applications. For example, consider BRADD-2, which allows complete design of simple bridges in approximately 120 hours. Assuming that salaries plus fringe benefits are increased from \$15 to \$20 per hour for CADD operators, and that the CADD system is operated for one shift per day at a cost of \$29.75/hour/workstation, then the cost of completing one design using CADD would be:

$$120 \text{ hours}(\$20/\text{hr} + \$29.75/\text{hr}) = \$5,970.$$

Dividing by the current wages for bridge designers would give the amount of work that could be purchased for this money using the current methods, or

$$\$5,970 / \$15/\text{hour} = 398 \text{ hours.}$$

Thus CADD is justified for this application if the current time to design the bridges is greater than 400 man hours per bridge. This may be lowered further if drafting time and costs are taken into account, and does not include other benefits that are harder to quantify. System costs can also be used to compare different applications to determine which will result in the highest productivity improvements and thus should be pursued more aggressively.

INDOT does not attempt to quantify CADD benefits because some of the benefits are hard to quantify and because of the sometimes unclear relationship between different functional areas for different CADD applications. However, it has been estimated by INDOT CADD staff that the benefits range from 10:1 to less than 1:1 for the various applications used in INDOT. Assuming an average of 3.6 to 1, as indicated in NCHRP Synthesis 161, would indicate a savings of over 3 million dollars per year.

The high costs and benefits associated with CADD necessitate a major emphasis on planning. Planning must be continuous to keep up with changes in agency needs and available technology. Proper planning will insure that the system meets needs and takes full advantage of the committed resources. Thus it is beneficial to develop rudimentary procedures of cost benefit analysis, even if all benefits can not be taken into account.

3.5 Recommendations for INDOT's CADD Program

Several recommendations were outlined in the earlier working paper to aid in the development of INDOT's CADD system (Vanegas 1989). These included:

- *Consolidating existing documentation into a single formal master plan addressing system goals, needs, facts, concepts, issues, hardware configuration, software applications, economic investment, and an implementation schedule.
- *Conducting a formal needs assessment.
- *Conducting an applications assessment.
- *Conducting a fact finding study.
- *A special study on a WAN to expand the system to all district offices.
- *A special study on a design consultant/INDOT CADD interface.
- *Special attention to Implementation and Interface issues between the different functional areas to increase use in areas different from road and bridge design and plan development.
- *Development of training and educational materials, courses, and delivery systems.

Since the preparation of the 1989 working paper, significant progress has been made by INDOT in implementing CADD. Suitable planning management and training structures have been established, and INDOT's knowledgeable staff continues to monitor and develop CADD capabilities. New applications are being evaluated, in addition to road and bridge design and drafting, and progress is being made on extending CADD capabilities to the district offices. In fact, the surveys received from other state transportation agencies indicate that INDOT is in the mainstream of what is being done

elsewhere.

INDOT's management structure allows the CADD staff to identify and address special issues and specific areas of concern as they arise. Since the first working paper, several discussions and meetings of the study team with INDOT's CADD task force have occurred. Three special issues that can aid in the continued development of the INDOT CADD system were identified. Proposals for the three areas were prepared, and INDOT is internally pursuing these issues. The proposals include:

- 1) Analysis of the various methods available for entering the Design Standard Details into the system, which currently consist of 180 sheets plus some miscellaneous details. Possible alternatives include:
 - *Scanning, including the work needed to make scanned images into usable drawings.
 - *Hiring consultants to redraw the sheets on the system.
 - *Drawing the sheets as time permits with available state forces. This alternative would involve a relationship between the number of people needed, amount of people needed, and amount of time to complete the job.
- 2) Performing a survey of other DOTs to determine how they handle transferring information with their consulting firms. This involves the following items:
 - *If DOTs provide survey data to consultants, do they offer electronic only, field book only, or both formats?
 - *Are project files transferred to the DOT in the specific format used by the DOT (translated by the consultant), or in various formats which are translated by the DOT?
- 3) Development of training modules for using GDS that will serve both as a refresher and on-line help for the individual. This will involve DEC Windows, and will determine what digital uses should be available to train their own people.

These are all very important issues. The literature indicated that developing CADD standards, digital data transfer standards, and training procedures are essential to the success of CADD. The experience of other states indicates that converting standard details and drawings to a CADD standards library significantly contributes to costs, and that one of the errors commonly made is to neglect this early in the planning process (TRB 1990). The TRB report also indicated that failure to develop adequate consultant/agency interface standards is another common obstacle to development of a successful CADD system. In addition, development of the training modules can be very beneficial in helping users to make better use of the system. It is important that INDOT continues to pursue these three areas.

In addition, INDOT may wish to investigate the use of complementary PC-based systems. The capabilities of these systems are continuing to improve, and they are much cheaper. There may be some applications where PCs are adequate, either networked or as stand alone systems. Specifying a format for exchanging CADD data may make the use of PCs for some applications more feasible.

It may also be beneficial for INDOT to develop rudimentary procedures for evaluating CADD benefits and costs. Even though all benefits can not be quantified, this will help determine which new applications are most productive, and will justify investment in CADD versus other advanced technologies.

CHAPTER 4: GEOGRAPHICAL INFORMATION SYSTEMS

As mentioned previously, geographical information systems (GIS) are derived from linking data in databases to geographical locations using the computerized mapping facilities of CADD. Spatial analysis can then be applied to generate functional maps and customized reports (Figure 4.1). The results of the state agency survey indicate that over two-thirds of the states are currently pursuing activities in the GIS area. Levels of involvement range from initial feasibility studies to working systems. Desired or available applications that are mentioned in the literature or surveys include:

- *Inventories (road, traffic, accident, bridge, etc.)
- *Executive Information Systems
- *Pavement Management Systems
- *Maintenance Management and Routing
- *Safety Management
- *Transportation System Management (TSM)
- *Travel Demand Forecasting
- *Corridor Preservation and Right-of-Way
- *Construction Management
- *Hazardous Materials Routing
- *Overweight/Size Vehicle Routing Permit
- *Accident Analysis
- *Environmental Impact Assessments
- *Land Slide Economic Impacts
- *Hydrologic Applications
- *Traffic Modeling
- *Transit Route Planning
- *Parking Management
- *Creating AADT Maps
- *Traffic Impact Analysis, and
- *Others

Abkowitz et al. (1990) stated that GIS applications involve various combinations of data retrieval, data

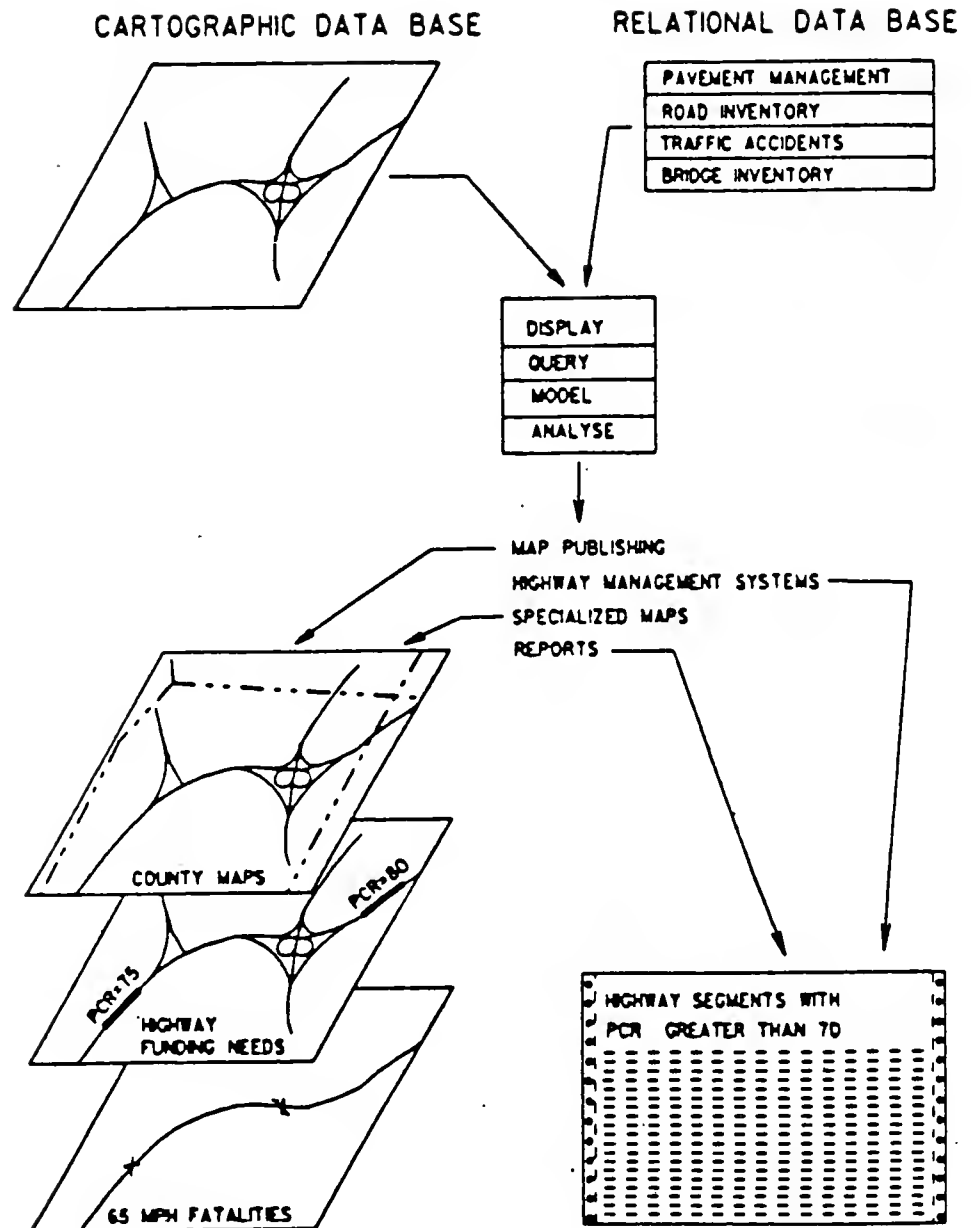


Figure 4.1: Structure of a Transportation GIS
(Source: Petzold and Freund 1990)

integration and data analysis. They grouped transportation GIS applications into five areas:

- *Pavement Management,
- *Traffic Engineering,
- *Planning and Research,
- *Bridge Maintenance, and
- *Field Office Support.

There is much available literature on GIS applications. A few are listed here: Simkowitz (1990) and Paredes et al. (1990) discuss pavement management applications; Abkowitz, Cheng, and Leposfsky (1990) discuss GIS for hazardous material routing; Lewis (1990) discusses transportation modeling applications; Simkowitz (1989) provides a summary of activities in the U.S.; and VanBlargan et al. (1990) discuss hydrologic applications.

4.1 General Requirements

As mentioned previously, CADD and GIS are closely related. Thus, many of the general requirements discussed for CADD systems apply to GIS as well. In addition, there are other issues not discussed under CADD that are important to GIS.

The general discussions on planning, management, and training that were presented under CADD are not reproduced here, although they are still valid. Instead, some of the issues touched upon earlier are expanded to include GIS, and new issues are brought up as well. The following paragraphs discuss some of the important issues in the development of GIS including:

- *Start-Up Issues,
- *Information Management,
- *Location Referencing Systems,
- *Map Scale and Accuracy, and
- *Other

4.1.1 Start-Up Issues

As with CADD, identifying potential applications is an important early step in system selection. Identifying applications where a GIS may result in increased efficiency and effectiveness is essential for development of needs, goals, and facts.

Petzold and Freund (1990) discussed the importance of the identification of potential applications prior to system selection. They found that this stage may require the most creativity and result in the most frustration for the agency's working group. It is important because it is preferable to select applications and find the best tool to fit agency needs, than to select a tool and be restricted to applications that fit the system. However, it is also necessary to find a balance between using tools in which there is already a large investment (i.e. existing CADD facilities), and risking the development of a new product which would involve large start-up costs and a new learning curve.

The Michigan DOT's (MDOT's) GIS Application Transfer Study (1989) provides an example of using applications to derive system requirements. The MDOT GIS working group performed 57 interviews with all department administration,

plus representatives from the FHWA and the Office of the Attorney General. The interviews were used to:

- *Familiarize the interviewees with GIS,
- *Provide for a two-way exchange of information concerning GIS,
- *Identify geoprocessing related activities, data types, and desired applications, and
- *Estimate benefits.

There were 335 separate geoprocessing activities identified. These were used to develop system requirements, based on data types, system capabilities, outputs, automated mapping, database, and other capabilities to be accommodated by the final system. This allowed for selection of equipment and development of an initial implementation plan.

Numerous potential benefits were identified. Only 12% of the identified benefits could be quantified, but this was more than enough to offset the estimated costs, which included hardware/software purchasing, data conversion, training, personnel, and equipment maintenance/leasing costs.

When identifying desired applications, information sources available from outside the agency should be considered. This includes coordination with other local or state agencies that may also be interested in a GIS. For example, the Pennsylvania DOT helped initiate a cooperative interagency group, with many other state agencies, in order to pool resources and reduce costs (Pennsylvania DOT 1990).

In addition, information may be available for purchase from the federal government or other sources. For example,

the U.S. Bureau of the Census Information offers Topologically Integrated Geographic Encoding and Referencing (TIGER) files, and the U.S. Geological Survey offers Digital Line Graph (DLG) files. These information sources can be purchased in digital format.

TIGER files were developed for use with the 1990 census data. These data will be referenced by latitude and longitude, and will provide information such as total population, population by time of day, and journey to work for transportation planning studies. A demonstration project was conducted in conjunction with the FHWA and the Bureau of the Census in 1988, in which the Columbia, Missouri, Department of Public Works used the files to develop a GIS containing a street sign inventory and an accident location file. The project showed that the TIGER files could be used to quickly create a base map for a GIS, create a GIS inexpensively, convert existing database referencing systems to latitude and longitude, and integrate different databases.

DLG files containing many types of useful information and attributes can also be purchased. Wang and Wright (1990) used the 1:100,000 scale DLG maps for Indiana to develop a GIS to be used as a tool for solving maintenance routing problems for INDOT. The base map has been developed, and an interactive filter program has been developed to manipulate and smooth the data. This is a resource INDOT could draw on to develop a GIS.

DLG and/or TIGER files can be used to develop the base map for a GIS, depending on the desired applications. They

are maps that have been digitized, with certain attributes attached to areas, vectors, or points. Other methods for developing base coordinates include surveying methods and digitizing or scanning maps in-house.

After applications have been selected, pilot projects can be useful implementation tools, as discussed under CADD. Petzold and Freund (1990) recognized the importance of pilot studies, and mentioned that limiting the size of the geographic area used for such projects, while using short-term software licensing and hardware leasing, can significantly reduce costs. However, they also caution that the risk avoidance implications of these small projects must be balanced against the need to allow for flexibility and future growth. Future growth may take the form of additional and larger information sources that need to be accommodated, or may involve links to engineering analysis tools that do not conform to traditional database formats. Examples include, engineering analysis software and expert systems.

Finally, care must be taken to not rely too heavily on vendors or consultants. Although quicker, this can result in a system in which the agencies staff are unable to unlock the full potential of the system. As with CADD, vendors and equipment must be carefully evaluated to fit the desired applications. Von Esson et al. (1990) compared the performances of several types of GIS workstation equipment. Lee and Zhang (1990) further discussed the hardware and software components of GIS.

4.1.2 Location Referencing System

A GIS is based on tying data to geographical coordinates, in terms of latitude, longitude, and possibly elevation. Usually an agency's existing databases are based on a variety of location referencing systems for different databases (i.e. latitude-longitude, milepoint, link-node, stationing, separate local coordinate systems). Thus it is necessary to convert existing data bases into a common referencing system to integrate data into a GIS. In addition, if external information sources such as TIGER or DLG are used, the location referencing system selected must be compatible with these sources as well.

In general, there are two methods available for integrating data into a common location referencing system: (1) mandating the use of a single location referencing system, in which all GIS databases must be changed to the same referencing system (which may mean that data collection activities in some areas must be altered), and (2) developing processes for converting existing location referencing systems to a common coordinate system, as databases are needed. The second option is usually used, due to the large investment in existing databases and data collection activities, as well as the potential to easily find coordinates in the future using GPS. For example, two common points and an elevation may be all that is needed to tie an existing coordinate system into another coordinate system. The coordinates of these points could be found quickly and easily using GPS.

4.1.3 Information Management

Information management deserves special consideration when developing a GIS. Many of the benefits of a GIS stem from increased data management capabilities that foster communication and reduce redundancies. In fact, GIS can be defined as an information management system that allows spatial analysis of the data.

Data to be included in a GIS will generally come from a combination of sources, including mainframe databases, computer networks, paper forms, and maps. Many different divisions and offices will be sources and/or users of similar types of data. It is important to coordinate between the diverse groups of users and sources. Each user and source will have its own needs, which must be balanced with the needs of other sources and users.

The Michigan DOT found that the key to success of a GIS was organizational in nature, and depended on information management. MDOT (1989), when identifying applications and system requirements, found that the 31 major types of data to be included in the GIS each had between 14 and 40 different users/sources.

Information conversion and coordination between a diverse group of users and sources is time consuming, tedious, and exacting. MDOT expects data conversion costs to be 2 to 3 times equipment costs, and Petzold and Freund (1990) reported that planning for information coordination may take as long as the conversion process itself. If no formal information management structure exists within the agency, an intra-

departmental administrative structure may need to be developed to insure success of the GIS.

Abkowitz et al. (1990) further discussed some of the key aspects of data management, including data organization, structure, collection, conversion, maintenance, and quality. They also noted that database management systems are central to the success of a GIS.

4.1.4 Map Scale and Accuracy

Accuracy is another important issue in the development of a GIS. The required location accuracies depend on the desired applications, and are different for planning, design, routing, and other applications. Petzold and Freund stated that an accuracy of 50 feet is sufficient unless information will be used directly in the design process. In general, more accuracy is more expensive.

Beaman (1990) discussed GIS accuracy. Accuracy depends on the source of the data, and there may be differences in accuracy within the GIS for different types of information, and where precision information has been input for special purposes. Both horizontal and vertical accuracies must be known by all potential users. There are three commonly used methods for communicating the accuracies of database information to the users. These are annotation, documentation, and education. Each has advantages and disadvantages.

Annotation involves keeping a separate field containing accuracy in the database, which is presented on the computer

screen when the database is loaded. This is obviously very convenient for the user, but is more expensive, and requires constant monitoring when data is manipulated. Documentation is the most common method, and refers to documenting accuracies in a user's manual or planning manual that is developed during data conversion, which is obviously inconvenient for the user. The third method is to use continual education and progress meetings to discuss accuracies, data sources, reliability, and system design with the users.

Data accuracies will be reduced by errors. Errors present in source documents used to create base maps (inherent errors) and errors produced through data capture and manipulation (operational errors) will both be present. Performing integrity checks and developing design specifications for generating data can mitigate these errors and improve accuracies.

4.1.5 Other

Only a few of the major issues were discussed above. Abkowitz et al. (1990), Simkowitz (1989), Lewis (1990), and Petzold and Freund (1990) discussed several other issues important to GIS development and provided lists of literature that can be consulted. These issues include segmentation, computing environments (centralized vs. decentralized), interdepartmental coordination, coordination with other agencies, the use of expert systems with GIS's management,

staffing, training, procurement, and the effect of existing CADD facilities (positive or negative) on the development of GIS.

Many of these subjects were discussed with CADD. Segmentation, however, was not. This refers to the method by which highways are broken into sections of homogeneous attributes for representation in digital format. Several difficulties arise in this phase of GIS development that must be addressed. O'Neill and Akundi (1990) further discussed segmentation as it relates to data conversion in GIS development.

4.2 Status of GIS in INDOT

INDOT considers GIS to be an application of CADD, thus placing both under the same management structure. This is not unusual as GIS is an emerging technology, and is not well defined. The state agency survey indicated that some states consider GIS to be more closely related to CADD, and others consider it an extension of database management, with some states placing heavy emphasis on advanced survey methods for collecting the positioning data needed for GIS. However, the literature indicates that GIS is more of an information management tool, and that there can be dangers when considering it an extension of CADD.

Currently INDOT is in the planning stage. A task force has been set up to develop GIS system requirements, a GIS plan, and an implementation schedule. System requirements are being developed using the results of a user needs analysis,

which is nearly completed. It defines the number of workstations needed for future CADD expansion.

INDOT uses IBM's IDMS (Integrated Database Management System) database. A user interface between IDMS and GDS is being developed to link database data to CADD. This is being done in-house. Some GIS users have already been trained in GDS.

It has been decided to use 1:100,000 DLG files for the base hydrographic, transportation, and airport maps. These files have already been purchased from the USGS, and an interactive filter program has been developed by Purdue University to smooth and manipulate map data. The TIGER files are to be used for political boundaries. These have been obtained from DNR at no charge, as INDOT cooperates with DNR on an informal basis.

Initially, a pilot project for transportation planning applications is planned. This will be followed by PMS (Pavement Management System) and Roadway Inventory applications. These are three of the applications most commonly mentioned by other state transportation agencies.

4.3 Costs and Benefits of GIS

The primary advantages of GIS arise from (1) the ability of maps to present complex information from a variety of sources in an easily understandable manner, and (2) the integration of data from many sources that have many different users into a single, consistent, and coherent system. These improved information processing and presentation capabilities

result in many benefits, including:

- *Reduction of duplication of collection, editing, storage, and reporting of information.
- *Improvement in the quality of presentation of information
- *Improvement in the timeliness, reliability, and consistency of information.
- *Improved decision making abilities.

These benefits are illustrated in Figures 4.2 and 4.3. The sign inventory data in the tabular form is difficult to understand. However, when merged with map and geometric data, it is much easier to understand and manipulate.

As with CADD, the benefits must outweigh the costs for each application to be pursued. Since a GIS is partially based on CADD, equipment costs are very similar to CADD equipment costs. If existing CADD software is to be used to develop the GIS, then some of the software acquisition and training costs can be neglected in the analysis. However, the data management costs of GIS must also be considered. The costs of converting data for use in a GIS can be estimated at between 2 to 3 times the equipment costs. This, however, is a one-time cost for a given application, whereas system management, equipment maintenance and training costs are continuous.

INDOT plans to install 10 GIS workstations during accelerated phase IV CADD expansion. Using the costs of the CADD stations as a benchmark, these workstations will cost approximately \$75,000 per workstation for hardware and

CONTROL SECTION 3403 NB M-66 SOUTH OF I-96

| STATION | LOC | CODE | CLR | SIZE | SUPPORT TYPE | # POST | MESSAGE |
|---------|-----|-------|-----|---------|--------------|--------|--|
| 372+00 | +R | M2VA | WBL | 21"X15" | U-CHAN | 1 | JUNCTION |
| 372+00 | +R | M1-1 | WBL | 24"X36" | U-CHAN | 1 | I96 ROUTE MARKER |
| 374+05 | +O | R4-9 | WB | 72"X36" | SPAN WR | 2 | KEEP RIGHT (ILLUM) |
| 375+30 | +L | R4-7 | BW | 36"X48" | U-CHAN | 2 | KEEP RIGHT SYMBOL |
| 377+75 | +R | D1-3 | WG | 8'X5' | WOOD POST | 2 | IONIA, GRAND RAPIDS, LANSING |
| 386+00 | +R | M1-2A | WG | 6'X6' | WOOD POST | 2 | WEST I96 RTE MARKER EAST I96 RTE MARKER |
| 388+00 | +R | W8-6 | BY | 30"X30" | U-CHAN | 1 | WATCH FOR ICE ON BRIDGE |
| 389+50 | +L | R1-2 | RW | 36"X36" | U-CHAN | 1 | YIELD |
| 389+60 | +R | R6-1 | WB | 36"X12" | U-CHAN | 1 | ONE WAY |
| 390+20 | +R | M3-1 | BW | 24"X12" | U-CHAN | 1 | NORTH |
| 390+20 | +R | M1-6 | WB | 24"X24" | U-CHAN | 1 | M66 ROUTE MARKER |
| 390+20 | +R | M6-1 | WBL | 21"X15" | U-CHAN | 1 | DIRECTIONAL ARROW |
| 391+00 | +R | W8-6A | BY | 36"X36" | WOOD POST | 1 | BRIDGE MAY BE ICY |
| 393+80 | +R | M3-4A | WBL | 24"X12" | U-CHAN | 1 | WEST |
| 393+80 | +R | M1-1 | WBL | 24"X24" | U-CHAN | 1 | I96 ROUTE MARKER |
| 393+80 | +R | M6-1A | WBL | 21"X15" | U-CHAN | 1 | DIRECTIONAL ARROW |

CONTROL SECTION 34044 RAMPE M-66 NB TO I-96 EB

| STATION | LOC | CODE | CLR | SIZE | SUPPORT TYPE | # POST | MESSAGE |
|---------|-----|-------|-----|---------|--------------|--------|----------------------------------|
| 7+10 | +R | R5-11 | BW | 24"X30" | U-CHAN | 1 | MOTOR VEHICLES ONLY |
| 7+10 | +R | R5-12 | BW | 24"X30" | U-CHAN | 1 | PROHIBIT MOTORCYCLE UNDER 125 |
| 20+00 | +R | R3-2 | BW | 24"X24" | U-CHAN | 1 | NO LT TURN SYMBOL |
| 20+60 | +L | W4-1 | BY | 48"X48" | U-CHAN | 2 | MERGE ARROW |
| 22+10 | +L | R6-1 | WB | 36"X12" | U-CHAN | 2 | ONE WAY ARROW |

Figure 4.2: Sign Inventory Data in Tabular Form
(Source: Michigan DOT 1989)

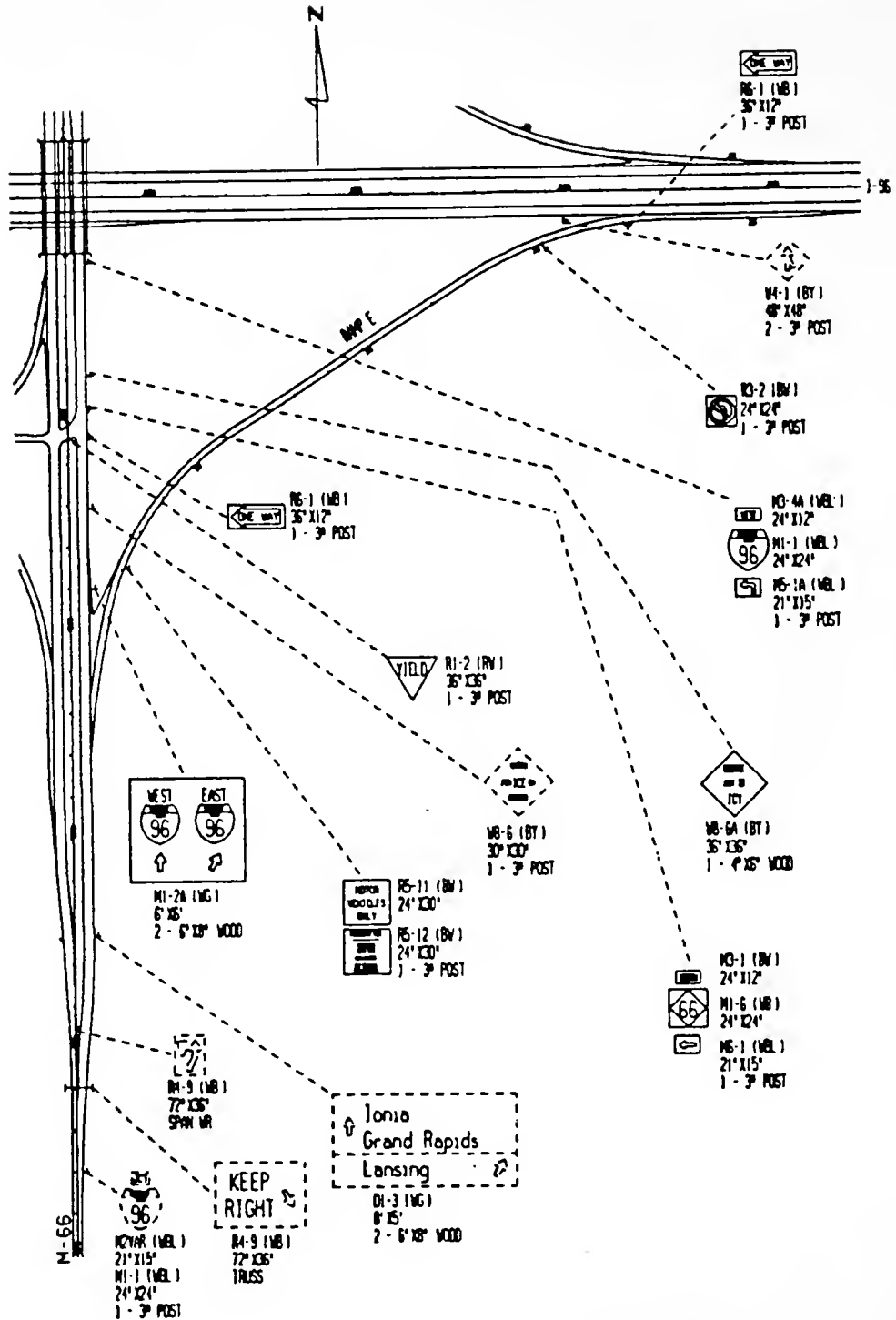


Figure 4.3: Sign Inventory Data Merged with Spatial Data
(Source: Michigan Dot 1989)

software, installed and licensed. Again, INDOT has no actual cost figures available, but the estimate of the cost of equipment is only \$50,000 per seat.

Assuming data conversion costs are 2 to 3 times equipment costs results in a cost of \$1.75 to 2.25 million for purchase, installation, and data conversion of a ten workstation system. Maintenance, management, and supply costs can be estimated as with the CADD system, and used to analyze the costs and benefits of the GIS system.

In INDOT, the GIS management structure is the same as for CADD, and is thus already in place. The purchase of DLG files is inexpensive. Transportation and hydrographic files for the entire state cost less than \$1,000. Thus these costs are neglected here.

The Michigan DOT (1989) estimated maintenance costs for its GIS system to be about 12.5% of the equipment costs. Supplies and utilities can be estimated at \$1,500 per workstation per year as with CADD. Thus the cost of the system can be estimated at approximately \$2 million for installation, purchase, and data conversion, plus an annual cost of around \$77,500 for a ten workstation system excluding user salaries.

GIS benefits are harder to quantify in the initial stages of a project than CADD. It is difficult to put an exact value on many of the benefits resulting from improved data management and decision making capabilities. Some benefits, however, can be quantified by estimating time savings. The Michigan DOT was only able to quantify about 12% of the

identified benefits of its planned GIS system, but this was enough to offset system costs after 2 years of operation.

4.4 Recommendations for INDOT

Geographic positioning and geographic data handling at INDOT were investigated and a working paper was prepared (Bethel 1990). Most of the recommendations presented in the paper were related to surveying, but many were related to GIS as well, including:

- 1) Establishment of a single state-wide high precision GPS-based network to be pursued with other state agencies, or development of a single Indiana State Plane Coordinate System. Currently separate local coordinate systems are used for different projects. A single system would allow for data collected in the future to be added to a GIS without the need for conversion between coordinate systems.
- 2) Integrating the nongraphic data into a GIS gradually, to avoid overlapping, redundancy, and conflicting geographic databases.
- 3) Development of standards for digital data exchange to allow sharing of data within the department, and data transfer between INDOT and consultants.
- 4) Investigation of the use of PC-based CADD/GIS systems. These low cost workstations may be appropriate for some applications, and could provide high performance/cost levels.

Since the preparation of this working paper, INDOT has addressed the development of standards for digital data exchange in relation to CADD. Establishment of a single high precision network based on GPS has also been proposed within INDOT.

Such a system would be of benefit to surveying, and it would allow all future activities to automatically be

consistent with GIS coordinates. However, it is important to remember that it may have some initial drawbacks for GIS. As Petzold and Freund (1990) discussed, mandating the use of a single location referencing system can disrupt existing databases, data collection activities, and applications that depend on other location referencing schemes such as milepoints or stationing. Thus detailed analysis and planning would be required before transferring to a single system, and it may be more desirable from the GIS standpoint to develop procedures for moving back and forth between existing location referencing systems and geographic coordinates. This could be done easily with the acquisition of GPS receivers.

Integrating nongraphic data into GIS gradually is an information management issue. As discussed previously, information management is essential to a successful GIS.

Investigating PC-based systems may be very worthwhile. INDOT is currently investigating user needs and applications. This may indicate some areas where PC-based systems may be sufficient. PCs can be networked to the system and used to display data and perform minor operations. "Micro" workstations that have more capabilities than PCs but cannot perform as many functions as complete workstations may also be worthwhile.

INDOT is already making considerable progress in GIS. The management structure for GIS is already in place, along with the training and planning capabilities. Developing an interface between IDMS and CADD is another important area where progress is being made. Furthermore, the experience

with CADD means that there is an intimate knowledge of current resources and constraints, which should make planning and development of GIS much easier.

INDOT is also cooperating with other agencies in Indiana that wish to use GIS, in order to reduce GIS development costs and insure that INDOT will be able to share data with other agencies. Coordination with DNR allowed INDOT to obtain TIGER files at no cost. It is likely that other local and state agencies, such as MPOs or the IMAGIS project in Indianapolis, would also be interested in coordinating GIS efforts with INDOT.

Progress in INDOT continues in identification of potential applications and user needs. As discussed previously, these are very important items. They should include identification of data types, outputs, inputs, map types, and the required capabilities of the completed system. This will allow identification of the required accuracies, development of system requirements, and estimation of potential benefits.

The above mentioned accuracies and data sources must be understood by all the future users of the GIS. This is best done through education and training, as annotation can be too expensive, and hiding them in a manual may hinder their availability. However, with a very powerful system, annotation may be easiest.

Information management is another important issue. Additional personnel may be needed to deal with coordination between diverse users and data sources, as well as for data

conversion. It would probably be beneficial to identify all potential data sources and users during the needs analysis, to improve coordination between these groups and eliminate redundancies.

There are several items related to the information management issue. These include data collection, conversion, correlation, integrity checks, updating, storage, communication, security, duplication, quality, and interagency data sharing issues. Therefore it may be beneficial to undertake a study on the information management implications of GIS within the department. It may also be necessary to develop additional information management administration capabilities. However, developing applications and integrating data gradually would allow data management issues to be addressed as they arise.

CHAPTER 5: ADVANCED SURVEY TECHNOLOGIES

There is currently a high degree of activity in the advanced survey and positioning area throughout the 50 states. This is mostly due to the emergence of NAVSTAR (Navigation System Using Time and Range) GPS (Global Positioning System). The state agency survey indicated that the majority of the states are pursuing advanced surveying technologies, and over half of these states are pursuing GPS to some degree, including both static and kinematic GPS applications. Automated survey data collection technologies and interactive photogrammetry are also being widely used.

5.1 GPS and Satellite Positioning

GPS is a satellite positioning system based on time and radiowave ranging. It was developed for the Department of Defense (DOD) which allows civilian uses. Wells (1986) discussed GPS and other satellite positioning systems in detail. A less technical and detailed discussion is presented here.

In GPS, the positions of satellites in space (ephemeral data) and the distances between the satellites and the points to be located (ranges) at specific times are used to determine point positions. Ranges are determined using receivers, which receive and process one-way radio signals originating from the

satellites. Satellite positions are determined by tracking the satellites orbits. Two way signals would be better for civilian applications, but one-way signals are used for military security.

Three phases (blocks) of GPS satellites are planned. The entire constellation will not be in orbit until after the turn of the century. This means that GPS must currently be used during "windows" when an adequate number of satellites are available over a given section of the Earth.

Accuracies of point positions determined using GPS depend on satellite configuration at the time of measurement, satellite and receiver clock inconsistencies, satellite orbit prediction accuracy, radiowave interference, and the application being used. There are five DOD control stations that track the satellites, synchronize satellite clocks, feed data to the satellites, and monitor and adjust their health and positions.

Accuracies continue to improve, and are much higher for relative or differential positioning. This refers to the use of more than one receiver, where a receiver's position is determined in relation to another receiver, instead of to the satellites themselves. Several states have developed fixed site receivers for use in relative positioning. States can develop their own tracking stations to improve orbit predictions, and thus increase accuracy.

Apart from GPS there are other advanced positioning systems available that are operated by the DOD and the Department of Transportation. These include Loran-C, OMEGA, Transit, VOR/DME, TACAN, ILS/MLS, and radiobeacons. These

systems, in general, will gradually be phased out as more advanced systems such as GPS become available. However, some will still be needed for use during GPS outages, or for checking GPS.

GPS itself will eventually be superceded by more advanced systems, such as GEOSTAR and NAVSTAT. These are systems being developed for commercial use. They are based on two-way communication, which will allow more accuracy and cheaper receivers, and will not be subject to interference from the DOD. Peak GPS use is expected to occur when the entire Block III constellation is in place, which will be after the turn of the century. Costs for GPS receivers will continue to drop as usage increases.

GPS applications can be broken down into two basic types: static and kinematic. Static positioning refers to the use of satellite positioning to determine the positions of stationary objects, and kinematic positioning involves the positioning of moving objects. There are many applications of GPS (Wells 1986), including:

- 1) Land-Based Applications
 - a) Surveying and Mapping
 - Surveying
 - Control Networks
 - Deformation Monitoring
 - Large Structures
 - Global (ie. plate tectonics)
 - b) Transportation and Communication
 - Automatic Vehicle Location (AVL)
 - Intelligent Vehicle Highway Systems (IVHS)
 - Freight and Fleet Monitoring and Control
 - Electronic Vehicle Navigation and Routing
- 2) Marine Applications
 - a) Surveying and Mapping
 - b) Transportation and Navigation

- c) Marine Sciences Applications
- 3) Airborne Applications
 - a) Surveying and Mapping
 - Photogrammetry
 - Laser Profiling for Direct Digital Mapping
 - Gravity Gradiometry
 - Laser Bathymetry
 - Radar Imaging
 - b) Transportation
 - En-Route Navigation
 - Approach Navigation
 - Freight Applications
- 4) Space Applications
 - a) Monitor and Control Satellites and Space Vehicles
- 5) Recreational Applications
- 6) Military Applications

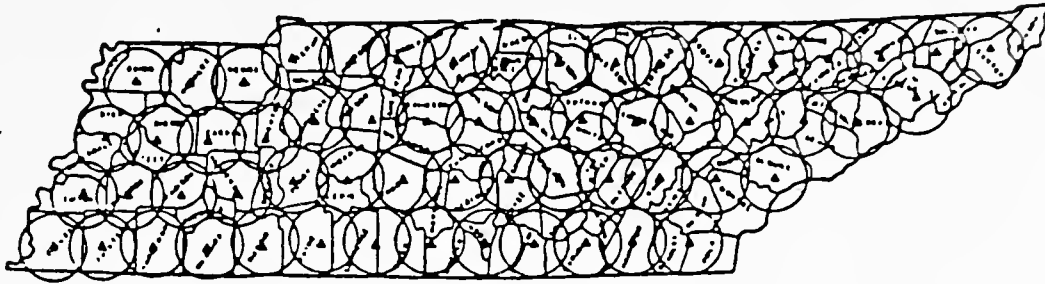
Of particular interest to the transportation agency are land-based and air-based surveying and mapping, and IVHS. IVHS will be discussed in Chapter 10. A brief discussion of surveying and mapping applications follows.

5.1.1 Surveying and Mapping Applications of GPS

The accuracy required for cadastral surveying is easily attainable by GPS. Widespread application of GPS in the field, however, depends on receiver capabilities that allow automated processing of GPS data. These capabilities continue to be improved upon.

Development of high precision control networks based on GPS can be done economically, and several states have established, or are in the process of establishing, such networks. These networks allow statewide positional data to be tied into a single coordinate system easily and accurately. This can have important GIS ramifications, as discussed earlier. The Tennessee DOT recently developed one such

network, involving 60 stations, for \$200,000 (Figure 5.1). Florida and Wisconsin are developing similar networks.



○ Fifteen Miles Radius Coverage

▲ T.D.O.T. Reference Network Point

Figure 5.1: Tennessee's High Precision GPS Network
(Source: Bethel 1990)

In lieu of development of a new control network, GPS could be used to locate projects in relation to the existing NGS monuments. A pair of receivers can be used to quickly and easily tie individual projects into NGS coordinates. However, with the increased use of GPS, control networks in the traditional sense will not be needed. GPS will make it possible to establish a control point anywhere.

Land-based kinematic surveying is another area being investigated. This involves mounting a receiver on a moving vehicle. One method, called semi-kinematic positioning, involves stopping the vehicle at various positions for a brief period while a measurement is taken. The NGS tested this method for surveying airport runways (Minkel 1989) and found that occupying stations for 2 minutes could provide subcentimeter accuracies.

Alternatively, less accurate positioning can be obtained without stopping. This method was used by the EPA for a GIS demonstration project in Los Angeles (Slonecker and Carter 1990). A vehicle equipped with a receiver drove the streets of the study area, digitizing the route followed, to assess the quality of the existing GIS digital transportation network. The data was used along with data from stationary receivers to adjust the GIS and improve its accuracy. Many states report the investigation of land-based kinematic GPS in vehicles for road inventory data collection.

Schwarz (1990) discusses a Canadian test for collection of roadway inventory data in which kinematic GPS was combined with on-board inertial measurement devices. The kinematic method was tested in a vehicle used for collecting videolog and digital inventory data for road maintenance databases. The vehicle was driven at 60 km per hour. It collected position data within 10-15 centimeters root mean square (RMS) error, curvature at better than 0.1 degree per 40 m, and slope to about 1% RMS. It is expected that these accuracies will be better than 5 cm, 0.2 deg./ 40m, and 0.1% in the near future.

Kinematic airborne applications are also being investigated at present. Of particular interest to the state transportation agency are photogrammetry applications. Before discussing GPS applications in photogrammetry, a brief and very general discussion of photogrammetry is presented. For more detail, Moffit and Mikhail (1980) provide a thorough photogrammetry text.

Basically, photogrammetry involves taking photographs, measuring the processed photographs, and reducing the measurements to some usable form such as topographical or planimetric maps. Apart from photography, radar imaging, radiant electromagnetic energy detection, and x-ray imaging can also be used. Aerial photogrammetry refers to the use of a precision camera mounted in an aircraft that takes photographs of the terrain in a given area as the plane flies over. Terrestrial and space photogrammetry are also used.

The majority of photogrammetric applications involve aerial photogrammetry using calibrated cartographic cameras that take a series of overlapping single frame photographs (strip). Strips can be overlapped to form blocks. Almost all phases of modern highway design, location, construction, and maintenance can be done wholly, or in part, by photogrammetry.

Large scale, small contour interval topographic maps developed from photogrammetry can be used as the basis for geometric design. Location surveys can be made with reference to points determined photogrammetrically, and the identification and location of boundary lines and corners can also be done photogrammetrically. All of the applications are too numerous to mention here.

Originally, photogrammetry was used to produce pencil-on-plastic-film maps, that were later redrafted in ink. As CADD developed, the pencil-on-film manuscripts were manually digitized into CADD format using large digitizing tables. Currently, CADD systems can be linked to stereo plotters that allow maps to be plotted directly from aerial

photographs into CADD format. This process is called interactive photogrammetry, and it is commonly used in state transportation agencies.

The advantage of photogrammetry is that it greatly reduces the need for costly field surveys. The costs associated with field surveys include personnel, travel, vehicle, weather coordination, land access coordination, and others.

Some field surveying is still necessary for photogrammetry. A certain amount of horizontal and vertical control, obtained through field surveys, is required to develop a stereoscopic model with a pair of overlapping photographs. Bethel (1991) suggested a practical minimum of 3 horizontal and 4 vertical points, although more is better.

In the past, all of these points would need to be located using field surveys. This tends to negate the primary advantage of photogrammetry: reduction in field surveying costs. However, in recent years mathematical techniques have been developed that allow many of the control points to be developed from a much smaller framework of ground surveyed points. These techniques are referred to as aerotriangulation, or "bridging". These techniques have been thoroughly tested and are widely accepted and used throughout the photogrammetry community.

With a few additional photograph measurements and some calculations, these techniques can be used to develop mapping control at significantly reduced costs. They can also be used for complete and accurate boundary and cadastral surveys, and

for locating arbitrary targeted points to determine their ground position for further field surveys, such as highway location, construction, and subdivision layout projects.

Airborne kinematic GPS is currently being investigated to further reduce the amount of field control required for photogrammetry. This involves differentially tracking the position of a GPS receiver placed aboard the aircraft throughout the flight. The resulting trajectories and positions of the antenna can be used to calculate the position of the camera when each photograph is taken (Figure 5.2). This can eliminate the need for any field control, although some would probably still be used as a check. Figure 5.3 compares the required amount of field control points for the three methods for a typical photogrammetry strip.

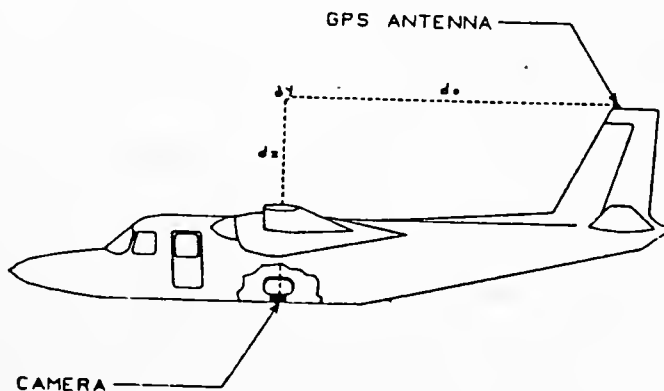
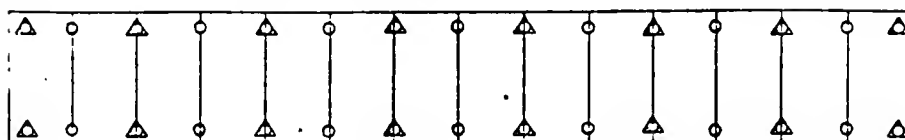


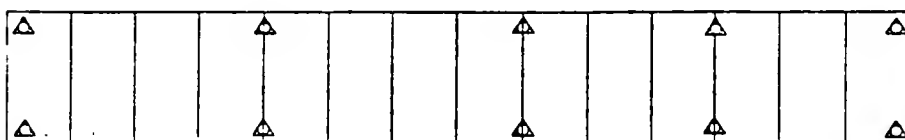
Figure 5.2: GPS for Photogrammetric Positioning
(Source: Lucas and Mader 1989)

The National Oceanic Service (NOS) recently tested this technology on two separate projects in cooperation with the Texas and Washington State transportation departments (Lucas and Mader 1989). In each case a series of photographs was

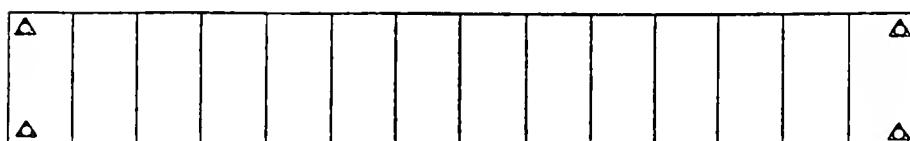
○ Vert. Control Point
 △ Horiz./Vert. Control Point



FULL FIELD CONTROL



FIELD CONTROL FOR A.T.



FIELD CONTROL FOR KINEMATIC GPS

Figure 5.3: Field Control Requirements for Photogrammetry
 (Source: Bethel 1991)

taken over an area of abundant ground control. The photographs were used to develop models 1) using the ground control without GPS positioning data, and 2) using solely GPS positioning data and no ground control. Some problems were encountered due to unfamiliarity with the technologies used, weather, and other reasons, and only one of the tests worked. However, discrepancies in the calculated camera location between the two methods were only about 5 cm in each coordinate, and discrepancies in calculated ground positions were even less.

Schwarz (1990) discussed semi-kinematic GPS, land-based kinematic GPS, and airborne kinematic GPS in more detail. Lists of further literature concerning these subjects are included in the discussion.

5.2 Automatic Survey Data Collection Systems

Automatic survey data collection systems comprise another widely used and growing technology. In the past, survey crews collected detailed notes by hand. These notes were then broken down later in the office, through calculations and manual plotting, to convert the data to useful formats. In automated data collection, an electronic data collector is link to the survey equipment. Data is automatically recorded. The data recorder is then linked to a CADD system in the office, which automatically uploads the survey data, performs the necessary calculations, and stores the data in CADD format. Automatic survey data collection is very important to a CADD system. In INDOT, keying data into CADD by hand was

found to take much longer than manual drafting of plan and profile drawings.

Thus, in general, a modern survey system contains electronic total stations, electronic field books (or data collectors), and data processing software. There are several vendors of advanced survey equipment. NCHRP Report 295 (1987) lists some of these vendors.

In more advanced systems, bi-directional data flow is possible. In other words, after the survey data has been used to develop a design, the design data can be fed back to the field equipment to aid with layout, greatly improving productivity.

5.3 General Requirements for GPS

Blair (1989) discussed some of the key issues in the development of GPS capabilities. These issues are very similar to the other technologies discussed previously. Key issues identified were equipment selection, training, planning, and testing.

5.3.1 Selecting Equipment

As with GIS and CADD, selecting the equipment needed depends on understanding the intended applications, existing resources, and constraints. Items in hardware selection that need to be addressed include equipment portability, required data processing equipment, types of computers needed, operating systems that the equipment uses, and number of computers needed.

Software items to be investigated include manufacturer software to assist in planning GPS surveys and processing data, adjustment programs to translate between desired coordinate systems, and other utility programs to aid in statistical analysis, data reporting, and other areas. Standards for digital data exchange need to be developed for GPS, as GPS will likely be linked to CADD and GIS, and data will need to be shared with consultants and within the department.

In addition to hardware and software, other equipment will also be needed. For example tribrachs, tripods, power sources, lighting, and transport vehicles. Lighting is required because at present satellite windows occur at night part of the year, and vehicles may be necessary to move crews quickly to take full advantage of the limited windows.

It is important to balance costs of additional equipment with the productivity added by the equipment. At least two receivers are needed, and a minimum of three are recommended. If simultaneous projects are envisioned, perhaps due to the limited hours of satellite visibility, then more receivers are needed.

Wells (1989) discussed the aspects of various brands of receivers in detail. In general, more flexibility in applications costs more. Al-Kadi (1989) developed a rating model for selecting GPS receivers (Table 5.1). The model includes user requirements (static vs. dynamic positioning, differential vs. point positioning, real time vs. postobservation data processing, required accuracies),

Table 5.1: A GPS Receiver Evaluation Model
(Source: Al-Kadi 1989)

| Number <i>j</i> (1) | Evaluation Factor (2) | Weighting Factor <i>w_j</i> (3) | Receiver's Evaluation Descriptor <i>d_{ij}</i> | | |
|----------------------------|-----------------------------------|--|---|---------------------------------|---------------------------------|
| | | | <i>A</i> <i>i</i> = 1 (4) | <i>B</i> <i>i</i> = 2 (5) | <i>C</i> <i>i</i> = 3 (6) |
| (a) Type | | | | | |
| 1 | Single/dual frequency | 0.2 | 1.0 | 0.0 | 0.0 |
| 2 | Code dependence | 1.0 | 1.0 | 0.8 | 0.8 |
| 3 | Carrier/code phase | 0.8 | 0.3 | 1.0 | 1.0 |
| 4 | Continuous/switching | 0.2 | 0.6 | 1.0 | 0.2 |
| 5 | Antenna performance | 0.3 | 0.6 | 0.8 | 0.3 |
| (b) Features | | | | | |
| 6 | Recording/observation length | 0.5 | 0.4 | 0.7 | 0.2 |
| 7 | Packaging | 0.4 | 0.6 | 0.8 | 0.6 |
| 8 | Size, weight, portability | 0.8 | 0.4 | 0.7 | 0.4 |
| 9 | Durability, ruggedness | 0.8 | 0.5 | 0.7 | 0.4 |
| 10 | Temperature range | 1.0 | 0.8 | 0.8 | 0.2 |
| 11 | Water/dust resistance | 1.0 | 0.8 | 0.8 | 0.5 |
| 12 | Electric power | 1.0 | 0.9 | 0.6 | 0.6 |
| 13 | Frequency standard, etc. | 0.4 | 0.4 | 1.0 | 0.6 |
| 14 | Software, utilities | 0.8 | 0.8 | 0.8 | 0.4 |
| 15 | Ease of operation | 0.9 | 0.5 | 0.8 | 0.2 |
| 16 | Maintenance, upgrading | 0.9 | 0.3 | 0.3 | 0.6 |
| 17 | Number, compatibility | 0.8 | 0.5 | 0.5 | 0.8 |
| (c) Procurement | | | | | |
| 18 | Cost | 1.0 | 0.6 | 0.7 | 1.0 |
| 19 | Availability, leasing | 0.5 | 0.6 | 0.3 | 1.0 |
| 20 | Warrantees, services | 1.0 | 0.5 | 0.7 | 0.8 |
| 21 | Company capability, reputaution | 0.5 | 0.1 | 0.8 | 0.8 |
| 22 | Training | 1.0 | 0.3 | 0.8 | 0.5 |
| 23 | Ephemens services | 0.5 | 0.3 | 0.6 | 0.8 |
| 24 | Other factors | 0.3 | 0.1 | 0.6 | 0.8 |
| (d) Overall Quality Rating | | | | | |
| — | $(q_j = \sum_{i=1}^3 w_j d_{ij})$ | — | 9.25 | 11.69 | 9.77 |

Note. Receivers, and their associated performance descriptor values, are hypothetical suggested here merely for illustration purposes.

receiver capabilities (frequencies received, code dependence, observable type, number of channels, antenna performance), receiver features (power requirements, data recording, size, ruggedness, ease of set-up and use, maintenance requirements, upgrading capabilities, compatibility), and costs (receivers, other hardware, software, training, maintenance, and vendor support services). The ability of equipment to process signals from other advanced satellite and radiowave positioning systems may also be important.

Before purchasing equipment, accuracy and flexibility claims should be checked. Other GPS users, the NGS, and the Federal Geodetic Control Committee (FGCC) can all be consulted to verify vendor claims.

5.3.2 Training

Although operating GPS equipment is not exceptionally difficult, analyzing the data and designing the surveys requires a significant amount of training in GPS and geodesy. Wells (1986) discussed survey design and GPS solutions in detail. In addition, existing survey crews will likely have little experience in operating even simple computers. Training must be considered before purchase, because it contributes to costs.

5.3.3 Planning

Planning is very important for successful GPS surveying. Satellites are only visible for 4-6 hours per day at present. Time is further constrained by travel time to survey

locations, and the longer observation times required for higher accuracy applications.

Contingency plans are also necessary. Satellites become inoperative from time to time, and need to be repaired by the DOD. Orbits are sometimes changed, and DOD may run tests or place restrictions that interfere with civilian use. Overhead obstructions can also pose a problem. For example vegetation may need to be cut in spring or summer. Other unexpected obstructions may crop up from time to time, and a careful record of obstructions should be kept.

5.3.4 Testing

It is necessary to fully test GPS equipment after purchase and training. This determines the accuracy and precision of the equipment. All of the available satellites should be tested in a variety of configurations. A range of environmental conditions should also be investigated. This will determine the weather and temperature ranges in which the equipment can be used. Blair (1989) found that snow, rain, and fog had little effect on accuracy, but that the equipment would shut down at very low temperatures.

5.4 Advanced Survey Data Collection Requirements

Paiva (1990) discussed key elements in the development of successful advanced surveying systems. His discussion includes preacquisition planning, discussion of the three components of automated surveying systems, and common pitfalls

in building these systems, with an emphasis on equipment compatibility and data communication.

5.4.1 Preacquisition Planning

Paiva lists several questions that must be answered prior to purchasing automated data collection equipment. Many of the issues raised by these questions are very similar to issues raised in discussion of other technologies. The questions were used to identify key issues that need to be addressed before purchase. Key issues include:

- 1) The ability of the system to fit in with existing methods and procedures. A systems inflexibilities may constrain the agency. Changes in operations that will be needed for a given system must be evaluated. Changing working procedures may effect morale.
- 2) Compatibility of the various components. This does not apply only to the reliability of hardware connections, but also to software connections, such as communications software.
- 3) Ease of use. This includes training, ease of learning to use the equipment, set-up, portability, and handling. Each component must be analyzed in the context of the other components it will be used with.
- 4) Vendor support. The issues of vendor support are similar to other technologies addressed in this paper. However, there is an added complication. If different components are obtained from different vendors, then vendors may try to pass the blame for failures to other vendors, and the problem will never get solved. Thus it is a good idea to use an obligation free test prior to purchase.
- 5) Accuracy of data transfer. The ability of the intended applications software to receive and use the data accurately and efficiently must be analyzed.
- 6) Bidirectional data flow. The ability to send data in both directions (from the field to the office for design, and from the office to the field for layout) greatly increases productivity.

- 7) Reliability. Down time must be planned for. Other users should be consulted to ascertain the reliability of each component. The entire system and each of the individual components should be studied in use.
- 8) Service availability and quality. This includes warranties during initial break-in, turn around time for repairs, and repair work warranties.
- 9) Expandability. Both the field and office components should easily be expanded or upgraded as needs change and the system grows.

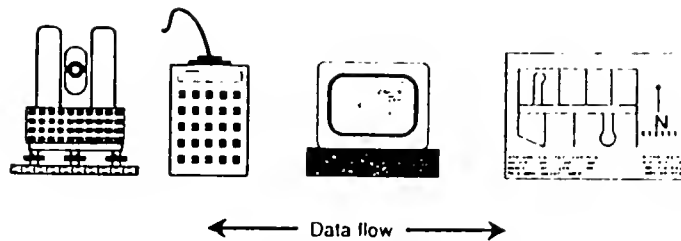
5.4.2 System Components

As mentioned previously, the three main components of advanced survey systems are electronic total stations, electronic fieldbooks or data collectors, and post survey processing software. Figure 5.4 compares the components of automated survey systems to traditional surveying methods.

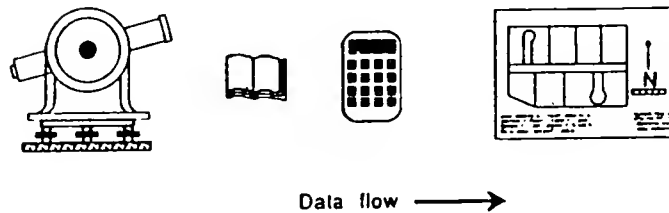
Paiva (1990) and NCHRP Report 295 (1987) discussed these components in more detail. There are many vendors and many different functions that can be performed by each of these components.

The total station takes measurements. It is usually controlled by the field book. Applications software and user interface with the total station are usually not that important because the stations will be controlled by the field notebook, which has much more power. Hardware controls and ease of use are more important, but all items should be evaluated.

Electronic field books can be simple data repositories, or can have powerful computing capabilities. Important issues concerning the data collector may include portability, communication abilities and protocols (with the total station,



The Modern Survey System



The Traditional Survey System

Figure 5.4: The Components of Traditional and Modern Survey Surveying Systems (Source: Paiva 1990)

data processor, modems, computers, plotters, printers, etc.), programmability, displays, manual recording capabilities, data storage capabilities, survey functions, database structure, available applications programs, special functions, units flexibility, error checking, input filtering, identifying equipment errors, application of environmental and instrument corrections, memory and power management functions, time and date functions, and the ability of the software to fit in with more than one way of surveying.

Postsurvey processing software can be very costly. Basic functions include handling of communications, error checking, data editing with the ability to recalculate affected data, file merging, data extraction, basic calculations from raw data, traverse checking and adjustment, and coordinate calculations. Many other functions are available. The functions required of the software depend on the desired applications. It is important that the software be able to translate data into the formats required by the applications software (CADD, GIS, etc.).

5.4.3 Common Pitfalls

Common pitfalls in the development of successful automated survey systems include communications incompatibility, hardware incompatibility, data format incompatibility, and data translation inconsistencies. The many vendors support many different communications standards, hardware standards, and data formats. Paiva discusses these problems in detail.

NCHRP Report 295 attempted to resolve many of these problems. It describes the development of the Integrated Survey Information Management System (ISIMS) which was developed to accommodate several types of data collectors and total stations. A standard data collection format was developed and software was prepared to translate from this format to existing applications formats such as RDS, IGrds, and Intergraph. The system was implemented in several states. AASHTO has also developed the Survey Data Management System (SDMS) to aid in managing survey data.

5.5 Status of Surveying in INDOT

Surveying practices in INDOT were investigated in the present study through a series of interviews with INDOT personnel. In two working papers the findings were summarized (Bethel 1990, 1991). The following discussion is an update of these findings.

The geodetic reference system of survey monuments in Indiana was found to be in poor condition. Many of the monuments have been destroyed or moved by land owners, developers, and service workers. There are also accuracy and consistency problems due to the 50 to 70 year age of parts of the system. These problems are not unique to Indiana. Other states face similar situations.

INDOT has determined that recovering existing monuments to run control into project areas is too costly. Thus separate local coordinate systems are used on individual projects. Establishment of a new reference network based on

GPS has been proposed within INDOT, and within other state offices. The cost of the network has been estimated at \$300,000, and it would involve approximately 90 stations. GPS would also be used for conventional surveying and bringing control into projects. Surveys has been trying to acquire funds to purchase GPS receivers for conventional surveying for some time. Three receivers are needed and it is expected that these will be purchased in one or two years at a price of \$20,000 each.

INDOT currently makes use of photogrammetric positioning techniques. INDOT has its own aircraft and camera, and uses these for an annual series of projects that are done internally. Aerial surveying is not done full time, and only about two weeks per year are spent establishing control for these surveys. At the time of the interviews, in autumn of 1990, all of the control points necessary for these mapping projects were located using field survey techniques (traversing and leveling). However, after meeting with consulting engineers, it was felt that INDOT is already using aerotriangulation techniques indirectly, through consulting services.

In addition, as discussed under CADD, Indiana uses automatic survey data collection technology. Several states listed the use of similar technologies under advanced surveying in the state agency survey. INDOT is considering purchasing laptop computers so they will not have to bring the data recorders in and plug them into the CADD system. Also, as discussed with CADD and GIS, INDOT is moving forward in the

development of digital data exchange standards and formats. This is related to surveying as well, and would allow data to be shared with consultants.

5.6 Costs and Benefits of Advanced Survey Technologies

The advantages of GPS for surveying basically boil down to higher precision, improved productivity, and lower manpower costs. Blair (1989) outlined the primary advantages of GPS for surveying:

- * GPS does not require intervisibility between sites, so extensive traversing can be eliminated, and sight obstructions and intervening property can be avoided.
- * Control can be brought in from many miles away without substantially decreasing accuracy of survey results.
- * The equipment can be used in inaccessible areas where "you can't get here from there" or it is not desirable to cut vegetation between points.
- * Potentially smaller survey crews can establish the same number of points per day.
- * Surveys can proceed in weather conditions that would delay conventional surveys.

The costs of GPS, as discussed earlier, are related to equipment purchase and training. A minimum of three receivers is usually required to maximize the investment. The INDOT Survey Unit is attempting to purchase three GPS receivers. With the capabilities and accuracies required by INDOT, three receivers will cost \$60,000 to \$80,000. Additional computers, software, and other equipment may be needed. Blair (1989) suggested that the minimum purchase cost for a three receiver system is closer to \$150,000, but prices have fallen since then.

In addition to equipment costs, training costs should also be taken into consideration. According to Steve Hull of INDOT Survey Unit, for advanced surveying technologies it takes only one to two weeks to train in the use of the equipment. However, it takes several weeks before survey crews learn to work together smoothly and began to unlock the full capabilities of the system. This is true for all advanced technologies, and is what is generally referred to as the "learning curve".

Survey crews in INDOT typically involve 5 to 6 men at average salaries of \$10 to \$12 per hour. Assuming 6 men at \$11/hour undergo training for four weeks, to account for initial training plus learning curve time, results in training costs of \$11,000 for one crew. If equipment purchase and instruction costs are estimated as \$100,000, and assuming maintenance costs are \$10,000 per year, then the cost of a GPS program in INDOT would be approximately \$110,000 initially plus \$10,000 annually for a three receiver system. The actual costs may be lower if equipment costs decrease and survey crews are already outfitted with and familiar with computers due to the automated data collection program.

Assuming that the potential reduction in crew size reduces crews by one man would result in a yearly benefit of around \$20,000. This by itself is enough to offset systems costs within 15 years, but the total benefits are potentially much higher. The ability to work without intervisibility between sites and in inclemental weather conditions would also increase productivity significantly. There are many other

benefits that are harder to quantify which should also be considered. Most notably, the ability to gain good control points on projects, tie projects into the GIS system, and develop a state plane coordinate system. INDOT does not currently have these capabilities, and must use separate local coordinate systems on projects.

The benefits of automatic survey data collection systems are similar to GPS. The benefits of these systems include improved accuracies, reduction in errors, time savings, and increased efficiency and productivity. In addition, there is no need for manual drafting of survey data, as this can be done automatically using CADD. This benefit can be attributed to CADD or surveys, given the close relationship of the two technologies. As with other advanced technologies, drawbacks include labor displacement, high capital costs, and department reorganization.

Paiva (1990) cited examples in which automatic survey data collection systems resulted in a 40% reduction in survey time and a 21% reduction in cost over traditional traversing methods. Traversing is the area where automatic data collection methods are expected to be least fruitful. He also found that small improvements in the procedures or software used with existing automated data collection systems could significantly increased time savings, on average 21%.

Hardware, software, and training are again the main costs of automated survey data collection. INDOT uses a TOPCON electronic total station and Lietz SDR24 data collectors that cost \$15,000 and \$4,000, respectively. Assuming training

costs are similar to those discussed under GPS, the initial cost to outfit and train a crew would be below \$50,000.

INDOT is just beginning to use automated survey data collection full time, and thus they are not able to calculate benefits. However, they feel that the benefits are significant. Assuming a conservative 20% reduction in time for a 6 man crew at \$11/hr would result in a savings of \$3,170 per month. This by itself would pay for one total station, one data collector, and training for a 6 man crew in ten months. Paiva found actual savings to be higher, over \$4,000 per month.

In addition, generating plan and profiles previously took a draftsman on average one week. Now the data collector can be plugged into CADD and the drawings generated in a few hours, saving on average 4 days. Four days at \$10/hour amounts to an additional \$320 savings for each set of drawings. If laptops were purchased and it was no longer necessary to bring the data collectors in to download data, additional time savings would be added.

The benefits of using aerotriangulation in photogrammetry result from a reduction in ground control survey time. INDOT speculates that a 50% reduction in the required number of control points could be achieved through aerotriangulation.

However, a considerable amount of the time spent establishing ground control for photogrammetry is used to get to the site and set up control. Once a survey crew begins establishing control points, adding a few extra points is not extremely expensive. INDOT estimates that the reduction in

time resulting from a 50% reduction in control points is only 20% to 30% once surveyors are set up at the site.

Since setting ground control points for photogrammetry is only done 2 weeks per year, the 20% time savings would amount to approximately 2 days per year. For a crew of 6 at \$11/hour this is equivalent to an annual savings of just over \$1,000.

This is a significant savings, but is much less than could be expected from GPS or automatic survey data collection, due simply to the limited need for photogrammetric ground control in INDOT.

5.7 Recommendations for Advanced Survey in INDOT

Two sets of recommendations were developed for INDOT in advanced surveying. Some of these have already been discussed in the chapters on CADD and GIS. The first set in 1990 included:

- 1) Working together with other state agencies and the federal government to establish a statewide GPS geodetic network. This would also be useful to DNR, county agencies, federal agencies, and private companies. Costs could be split between agencies. Working with NGS to fund a position known as "Geodetic Advisor" is a prerequisite to obtaining NGS assistance, and may be a prudent investment.
- 2) As an alternative to 1), developing a standard Indiana State Plane Coordinate System as opposed to using local project coordinates. This could involve occupying existing NGS monuments with GPS receivers, and differentially moving control into individual project areas.
- 3) Adopting aerotriangulation for control in photogrammetric projects instead of providing full field control for each model. This has been well tested by others, and would reduce survey costs.

As discussed previously under GIS, item one may have wide ranging impacts on existing databases, data collection activities, and applications. Therefore it should involve careful analysis and planning.

Acquiring GPS receivers, as proposed in item two, would be an appropriate first step in the development of a GPS network. This would aid in moving back and forth between existing coordinate systems and the single coordinate system that would be required for GIS, when necessary, and would allow projects to be tied into the existing state plane coordinates to in the near future. It would allow for verification of the accuracy of base GIS map data, and would also provide a way of gaining experience with satellite positioning technologies. After adequate experience is gained, a more accurate coordinate plane would be developed using GPS. This network would include some of the existing NGS monuments plus additional monuments as needed.

Establishing a statewide reference network is inevitable, due to the recent increase in GIS activity. Other agencies and companies will likely desire data from INDOT for use in GIS. INDOT should take the lead in developing such a network, to insure that it serves INDOT's needs, and strive for cooperation with other parties to reduce development costs.

INDOT's automated survey data collection program is well underway. This is the advanced survey technology that offers the highest benefits and lowest costs. GPS also offers high potential benefits. A GPS program should be developed in the near future.

Using aerotriangulation is a somewhat older technology, and does offer significant benefits. It should be investigated as funding allows, but does not offer as high of a return on investment as GPS or automated data collection due to the limited scale of photogrammetric mapping within INDOT. For this same reason, airborne kinematic GPS for photogrammetry would also offer lower benefits. However, this would place INDOT in the forefront of advanced positioning technologies.

After further discussions with INDOT, the original recommendations concerning photogrammetry were expanded. Two projects were proposed whereby INDOT could investigate the reduction of field control in photogrammetric projects through aerotriangulation and kinematic GPS (Bethel 1991).

A demonstration project was proposed for checking aerotriangulation versus INDOT's usual field control method. An upcoming project containing at least 12 models would be selected, and INDOT would perform the field survey in the usual manner. A contractor would then use the same photographs and a subset of the field survey control points to calculate coordinates for all pass points and the remaining control points. The results would be compared to determine the accuracies of aerotriangulation.

Personnel from Purdue University could verify the results independently, at the Purdue Photogrammetry Lab. They could also assist in arranging work with the contractor, and demonstrate aerotriangulation, photo measurement, and computational techniques.

During the project, careful records on expenditures would be kept to compare the two techniques. The assistance of Purdue could be used in quantifying the effort and expenses. If INDOT then wishes to acquire aerotriangulation capabilities, Purdue could assist in the acquisition of equipment, which has been described in more detail in the working paper (Bethel 1991).

The working paper also discussed kinematic airborne GPS for photogrammetry using a fixed receiver on the ground and a receiver attached to the aircraft, as in the NOS project discussed earlier. This technology is still in the experimental stage.

A more ambitious project would involve placing three GPS receivers on the aircraft in order to obtain orientation and attitude in space, and the coordinates of the exposure station.

INDOT may be interested in experimenting with these technologies. It is in a good position to do so, since it has its own aircraft and routinely undertakes mapping projects. Projects in this area would put INDOT in the forefront of innovative approaches to positioning.

CHAPTER 6: EXPERT SYSTEMS

As mentioned in Chapter 2, expert systems evolved from research in artificial intelligence (AI). AI is a field of computer sciences concerned with reproducing human intelligence. It can be divided into three areas: developing programs that read and speak conversational language, developing smart robots that recognize objects, and expert/knowledge-based systems. Expert systems attempt to solve problems by simulating the reasoning process of human experts.

The use of expert systems has increased rapidly during recent years, and there is a wide body of literature on expert systems in civil engineering. A variety of applications have been developed for use on mini- and microcomputers. Less literature exists concerning mainframe applications because applications that use large amounts of data can be less efficient at present. This section gives a general discussion of expert systems, including identification of the components of expert systems, discussion of the types of problems that can be solved with expert systems, description of expert system development tools, discussion of merging expert systems with other technologies, identification of expert system applications, discussion of the general requirements for developing expert systems, and development of recommendations for INDOT in the development of an expert system program.

6.1 Components of Expert Systems

Terry (1991) and the FHWA report TS-88-022 (1988) discussed expert systems from the engineering manager's and developer's perspectives. In general, as depicted in Figure 6.1, expert systems consist of:

- * A Knowledge Base,
- * An Inference Engine, and
- * A User Interface.

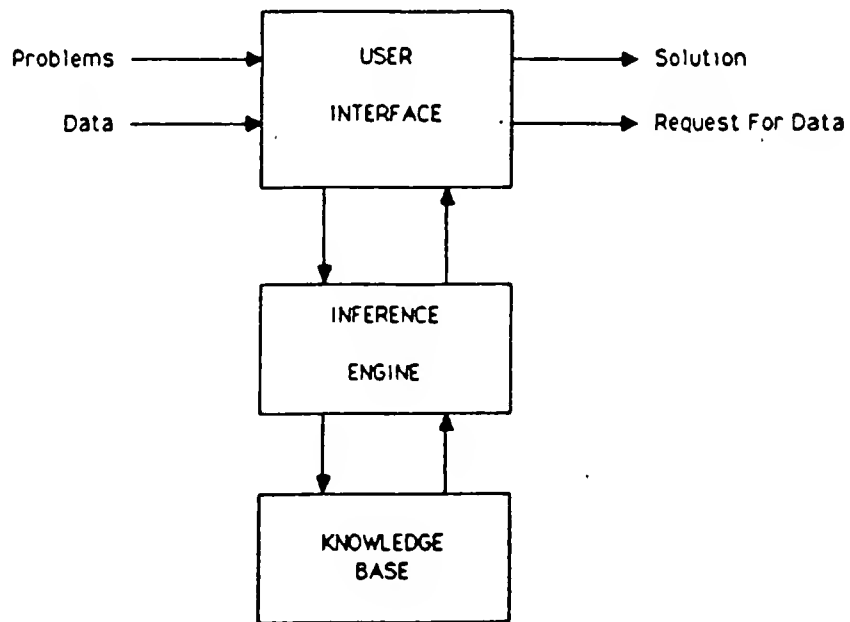


Figure 6.1: Block Diagram of an Expert System
(Source: USDOT 1988)

6.1.1 Knowledge Base

The knowledge base stores facts and rules, where facts refer to known truths to be represented and rules are conditional (if-then) statements. Uncertainty can be included in the knowledge base using certainty theory or probabilistic methods. The information in the knowledge base can be accessed and altered through the user interface. A number of knowledge representation schemes have been developed for expert systems. The most common are rule-based and frame-based representation schemes.

Rule-based schemes represent knowledge in one of two ways: as a collection of facts or a collection of condition-action (if-then) rules. Facts may take the form of attaching attributes to objects, or defining the relation between objects.

These methods of knowledge representation lend themselves well to deductive reasoning inferencing techniques. Deductive reasoning inferencing techniques may be forward-chaining, in which new facts are derived from existing facts or rules, or backward-chaining, in which an attempt is made to prove an assumed conclusion by searching existing facts and rules. Forward-chaining is more efficient when there are few initial conditions, and backward-chaining can be used when the outcomes are few and are easy to identify. Some expert system inferencing tools combine forward and backward-chaining approaches, which can be more powerful, but are harder to use. An inference chain is presented in Figure 6.2.

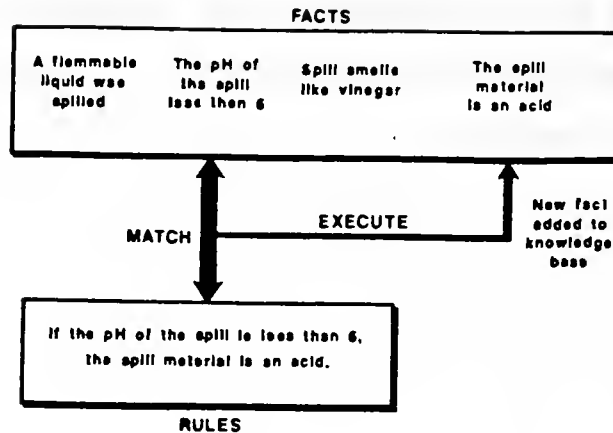


Figure 6.2: An Inference Chain
(Source: Faghri and Demetsky 1988)

The advantage of rule-based schemes is that deductive reasoning more closely models the way that many experts solve problems. Thus they are easier to understand and use. They work best when knowledge can easily be represented as unstructured facts and rules.

The frame-based scheme uses frames, which are descriptions of objects that contain slots where information about the object can be stored (Figure 6.3). Frames can be linked together in a tree-like hierarchy, where information in a lower frame can be automatically inherited from higher frames. Each slot can have a variety of procedures attached, that are executed when information in the slot is added, removed, or called upon by the inference engine.

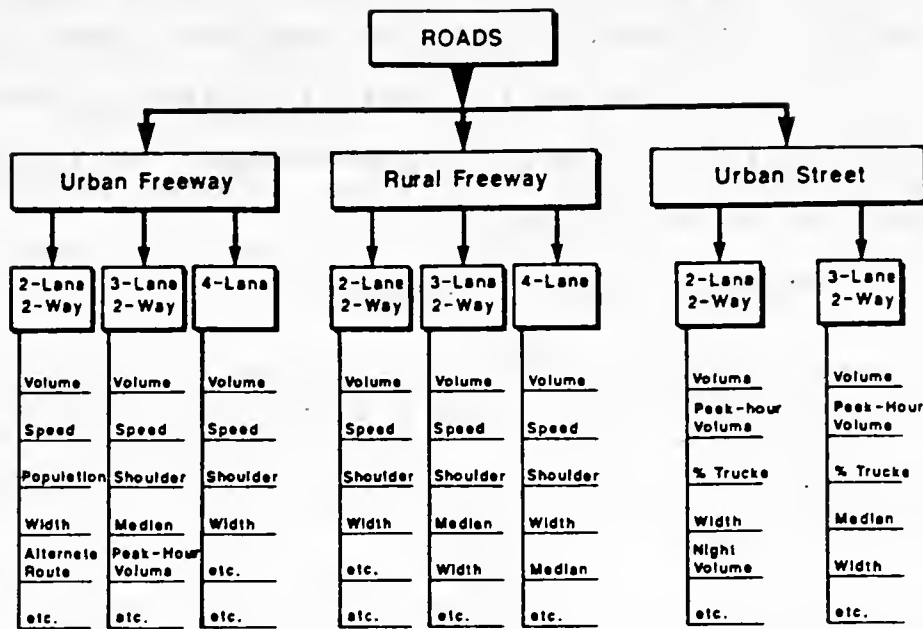


Figure 6.3: A Frame Based Network
(Source: Faghri and Demetsky 1988)

Frame-based systems are more applicable to problems with highly structured knowledge. Although more difficult to learn and understand, they allow knowledge to be structured in logical packages. The use of frame-based knowledge bases is growing, but rule-based schemes are still the most widely used.

The appropriate knowledge representation scheme depends on the problems to be solved. Some expert system tools allow both rule and frame-based representation schemes. There are other representation schemes that are less widely used. Faghri and Demetsky (1988) discussed knowledge representation schemes in more detail.

6.1.2 Inference Engine

The inference engine uses the rules and facts (problem domain knowledge) from the knowledge base, along with information input by the user, to solve problems. Thus it contains the problem solving knowledge. The inference engine performs several functions:

- *Selecting rules to examine,
- *Evaluating rules,
- *Generating new facts from existing rules and facts,
- *Retrieving facts from the knowledge base and the user,
- *Generating solutions.

As mentioned previously, the inference engine can use forward and/or backward-chaining. In forward-chaining the available rules and facts are iteratively compared. When a rule is consistent with the facts, it is applied, creating new facts, and initiating another iteration. This continues until a solution is achieved or no new facts can be derived. In backward-chaining it is assumed that a conclusion is true. Then rules are evaluated to determine which facts must be true for the assumption to be valid.

6.1.3 User Interface

The user interface allows the user to specify a problem to be solved, specify the data to be reported, alter the knowledge base, and request explanations from the expert system. It also provides the means by which the system requests input information and reports solutions.

The most common input mechanism is the menu, and the most common output is tables and lists. Lists of alternatives can be ranked when uncertain knowledge is represented. Some systems allow graphical output. Other methods of communication being investigated include natural language capabilities and videodisc technology.

6.2 Types of Problems Solvable by Expert Systems

Many researchers have developed guidelines for determining what types of problems can be solved using expert systems. Han and Kim (1989) suggested:

- 1) Genuine experts must exist who can articulate their problem solving method.
- 2) Experts must agree on solutions.
- 3) The task must not be poorly understood.
- 4) The problem should take a few minutes to a few hours to solve.
- 5) No controversy over problem domain rules should exist.
- 6) The problem should be clearly specifiable and well bounded.
- 7) The problem solving should be judgmental in nature and not numerical.

Terry (1991) expanded upon these requirements. The problem should not be trivial. There should be a definite payback, and the problem should be important to the agency now or in the near future. It should involve small amounts of mathematical computations and should be difficult to solve using other methods. The knowledge should lend itself well to representation as if-then statements and involve thought processes instead of physical ability, common sense, or

feelings and emotions. There should be high confidence of success and a way to validate solutions and measure impacts.

The FHWA report (1988) divided suitable problems for expert systems into six categories:

Diagnosis

Examining a systems outputs/symptoms to infer causes, and then remedies (e.g. PMS).

Interpretation/Classification

Identifying an unknown entity by comparing input features/attributes to those of a set of known entities. For example choosing an appropriate delivery system for a new technology would involve matching the features of known delivery systems with the features of the target audience.

Prediction/Forecasting

Forecasting the future state of a system based on the existing state and a knowledge of past events. For example predicting accident rates for changes in a roadway based on past experiences.

Design

Deriving the specifications on how a system is to be built from knowledge about the basic components that may be used, the environment, and constraints on the final system (e.g. pavement design).

Planning

Using knowledge on the environment, component actions of the plan, and constraints, to select actions that move from an initial state to a goal state. For example in developing a work zone traffic safety plan: the goal would be safety and reducing disruption to traffic flow; possible actions would include placing and removing signs, pavement markings, and channelization devices; and the environment would include traffic flow, traffic control, and geometric data.

Monitoring

This involves analyzing a systems outputs and implementing corrective measures if the output crosses specified boundaries (e.g. automated signal timing control).

6.3 Tools for Developing Expert Systems

There are many types of programming languages and computer support packages available for developing expert systems. These are generally grouped into three categories: programming languages, knowledge engineering languages (shells), and system-building aids. Shells are the most commonly used, because of ease-of-use. However, different types of problems or knowledge representation schemes may be more amenable to other tools.

6.3.1 Programming Languages

Expert systems can be developed using problem-oriented programming languages such as FORTRAN, Pascal, or BASIC.

These languages have been used to develop expert systems, but are not used for extensive applications. They are primarily designed for rapid calculations, algorithms, and managing large amounts of data. Thus they do not have features that lend themselves readily to expert system development.

AI is based on symbolic information processing, which involves using symbols and special techniques to model human reasoning. This may include heuristics (empirical knowledge), defining relationships between objects, uncertainty modeling, conditional statements, and relative amounts (low, moderate, high). Many symbol-manipulation or object-oriented languages have been developed that include special features to facilitate symbolic information processing. These languages are widely used for expert system applications.

The most commonly used symbol-manipulation language for developing expert systems is LISP, from LISP Machine, Inc. There are many others, including INTERLISP-d and SMALLTALK-80 (Xerox Corp.), Prolog (Quintus Computer Systems, Inc.), GCLISP (Gold Hill Computers, Inc.) and many others.

6.3.2 Shells

Expert system shells contain knowledge base development aids, inference engines, user interfaces, and other expert system development aids. They make expert system building easier, and it is not necessary to learn a symbol-manipulation language to use them. Shells can be skeletal or general purpose systems.

Skeletal systems are designed for limited classes of problems, and thus lack generality and flexibility. However, they are easy and fast. General purpose shells, on the other hand, can handle many types of problems and also allow greater access to the knowledge base, although they may be more difficult to use. Figure 6.4 illustrates the components of an expert system shell.

There are over 50 low-cost microcomputer based expert system shells available on the market. Rosenthal (1988) and Finnie (1988) listed and discussed available expert system shells. These shells have widely ranging features and prices, and come from a variety of vendors. Selecting the appropriate shell to match a problem is a very important decision. According to Terry, some of the features offered by typical shells include:

- *Built-in inference engine with choice of chaining methodology.
- *Highly interactive environment for development and testing including menus and prompts.
- *Debugging and value checking aids.
- *Consistency checking.
- *Rule prioritization capabilities.
- *Interaction with other data sources including access to external operating systems and spreadsheet and database files. This may be done either by direct access or export/import functions.
- *Ability to create and display graphics or interface with graphics files and programs.
- *Mechanism for handling (input and calculation of) uncertainties.
- *Simple but comprehensive rule language with an integrated window-oriented editor.

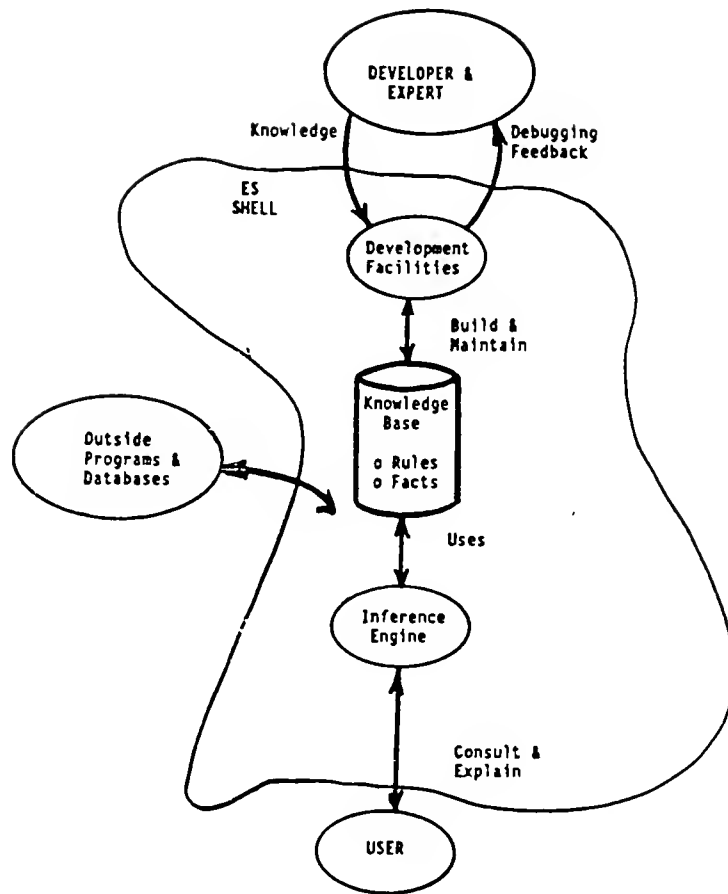


Figure 6.4: An Expert System Shell
(Source: Terry 1991)

- *Explanation facilities to describe how and why the expert system arrived at an answer, showing the sequence of rules involved.
- *On-line help.
- *Security provisions to protect data and programs from unauthorized modification.
- *Manuals are usually written in tutorial style with many examples.
- *Report generation and customization for screen and printed data.
- *A license agreement that allows unlimited, free run-time versions of applications that use the shell.

6.3.3 System Building Aids

There are a variety of system building aids available commercially to help with expert system development. These are software programs to aid in system design or knowledge acquisition. Design aids help to establish frameworks for the system, and knowledge acquisition aids help in transferring knowledge rules and heuristics from human experts into the knowledge base. Some of these aids are EXPERT-EASE (Expert Systems International), RULE-MASTER (Radian Corp.), and TIMM (General Research Corp.). Some system building aids may be included in commercially available shells.

6.4 Integrating Expert Systems With Other Technologies

Expert systems can be integrated with other technologies to improve their efficiency or create "intelligent" systems. Han and Kim discuss the relationship between expert systems and computer-based information management technologies. The focus of their discussion is on urban planning and urban

information systems, but it is applied more generally here. Types of information management technologies that can be coupled with expert systems include:

- *Database Management Systems (DBMS),
- *GIS, and
- *Decision Support Systems (DSS) and Executive Information Systems (ESS).

6.4.1 Database Management Systems

DBMS are computer software for managing data. They typically organize, store, modify, and perform limited calculations on data. They can usually process data and output reports as well. Integrating DBMS with expert systems can increase the power of both expert systems and database management systems.

Lee and Galdiero (1989) developed a pavement management expert system (PMES) that allowed an expert system to be integrated with an existing DBMS, thus merging the expert system smoothly into the existing pavement management system. The system was designed to select maintenance activities for local governments, which had no available experts. It used a commercially available microcomputer shell and DBMS. Run times could be prohibitive for merging large expert systems with large mainframe based databases.

Lee and Galdiero (1989) stated that integration of expert systems and DBMS can be loose or tight. In loose coupling the expert system is attached to the DBMS as an application program. In tight coupling the two systems are completely

integrated. This can involve an expert system with built in data management capabilities, or an intelligent DBMS with programming or internal expert system capabilities.

Microcomputer-based expert systems shells that offer DBMS integration capabilities are commercially available. Petersen (1988) evaluated the capabilities of available expert system shells for integration into conventional computer environments.

6.4.2 Geographic Information Systems

GIS are a union between DBMS and computer aided mapping (CAM) technologies. A GIS differs from a DBMS by allowing spatial analysis of the data, and differs from CAM in that it supports not only mapping but geographic analysis. Many geographic modeling tasks require user expertise that can better be provided by experts. The integration of GIS and expert systems could improve the power and efficiency of many GIS applications.

Abkowitz et al. (1990) discussed the integration of these two technologies. Research in this area is relatively new. Many applications of expert systems in GIS are being approached by a number of researchers. These include automated map design, automated feature extraction, database management, user interface, geographic DSS, and selecting map overlay combination methods. These applications are at the forefront of GIS research.

6.4.3 Decision Support and Executive Information Systems

DSS can be viewed as a DBMS with a model base attached.

The model base uses data from the database as input to various models, including operations research models that simulate, optimize, or make predictions. The DSS is accessed through a user interface. The user calls up mathematical models and runs them using the data in the databases. This allows quick analysis of large amounts of data.

EIS can be viewed as a type of DSS for executives and upper level management. The state agency survey indicated that several states are currently pursuing EIS technologies. These programs analyze data and present summaries to executives who do not have time to analyze it themselves.

Integrating expert systems and DSS can create more powerful and useful systems, sometimes called expert decision support systems (EDSS) or intelligent decision support systems. The combination of these technologies can involve integrating expert systems capabilities into conventional DSS, or attaching a modeling capability to a conventional expert system.

These integrated systems can help DSS users select appropriate models, interpret results, integrate judgmental elements in a model, aid in building simulation models, improve the user interface, translate qualitative data into numerical input, and translate numerical output into qualitative concepts.

6.5 Expert Systems Applications

Expert systems are quickly becoming an alternative to traditional programming techniques. When time, budgets, or

available personnel are constrained, expert systems can be very valuable tools. A wide variety of applications have been identified, and there is a significant amount of literature available on specific applications that have already been developed. A report prepared by the U.S. Army Corps of Engineers (1986) summarized several existing expert systems in transportation engineering.

Some specific applications that are being developed include: several pavement maintenance, management, and rehabilitation applications (Lee and Galdiero 1989; Tandon and Sinha 1987; Aougab et al. 1989; Hajek et al. 1987; Ritchie et al. 1987; Hall et al. 1988; Zuk 1986); real time traffic control and IVHS (Ritchie 1989; Chang and Tang 1989; Radwan and Goul 1989); bridge management (Zuk 1986, 1987; Virginia 1989); retaining wall failure diagnosis, rehabilitation design, and cost estimation (Adams et al. 1988); compactor selection (Touran 1990); selection of measures to improve intersection safety (Seneviratne 1990); selecting traffic controls for highway work zones (Faghri and Demetsky 1990); regulating heavy vehicles (Robinson, 1990); traffic signal setting assistance (Zozaya-Gorostiza and Hendrickson 1987); noise barrier design (Harris et al. 1989); regulating hazardous materials and responding to incidents (Hobeika et al. 1988; Wilson et al. 1990); evaluating and notifying hazardous waste generators (Knowles et al. 1989); selection of soil improvement techniques (Chameau and Santamarina 1989); automating building and bridge design and selecting building repair techniques (Bedard and Gowri 1990; Jones and Saouma

1988; Adeli and Balasubramanyam 1988; Kalyanasundaram and Udayak 1990); bridge inspection and asphalt paving inspection training and advising (Melhem and Wentworth 1990; Williams et al. 1990); construction project scheduling aids (Benjamin et al. 1990); evaluating and prioritizing railroad highway grade crossings (Faghri et al. 1988); transportation contingency and disaster planning (Braun and Machado de Sa 1988); interactive graphics intersection design aids (Chang, 1989); and analysis and design of urban transit networks (Janarthanan and Schneider 1988).

This is by no means a comprehensive list. There are other areas where expert systems have been developed, and where possible uses of expert systems have only been identified. However, it gives a good idea of the diversity of expert systems applications being used, and where they can be applied.

6.6 General Requirements for Developing Expert Systems

FHWA report TS-88-022 (1988) outlines a methodology for developing expert systems. The report identified four categories of participants who must be involved in the development process for successful expert system development. These include the system "champion" or advocate, the end users, the domain expert(s), and the knowledge engineer. Each participant has certain tasks.

The champion (or task force) must identify the need for the system, identify the intended user community, define the problem domain, define the benefits, identify the experts,

choose a knowledge engineer, and plan for maintenance of the finished product.

The end user's input is necessary for defining the skill level of the user community, providing information on how problems are addressed in the field, providing advice on functions that must be accommodated for the system to be accepted by the users, and testing and promoting the system once it is finished.

The domain expert is the expert whose knowledge is modeled. His problem solving ability serves as a model. He must also assist in quality control to make sure the system is accurate. This will involve design of a comprehensive set of test questions for use in verification.

The knowledge engineer models the experts knowledge. He must also implement the model of the expert's knowledge, make sure the implementation is smooth, document the system, and test the system.

The FHWA report (1988) also outlined several steps to follow in the development process. These include:

- *Identify the need for an expert.
- *Clearly define the application for the system.
- *Identify the expert.
- *Identify the expected benefits.
- *Knowledge engineering.
- *Design and development.
- *Verification and validation.
- *Selecting the tools.
- *Distributing and maintaining the system.

6.6.1 Identifying a Need

A need for an expert system must be identified. The problem must also fit the guidelines outlined in Section 6.4.2. In addition, several conditions are listed that should be true in order to justify an expert system. These include:

- 1) All participants must be identified and committed to the success of the project.
- 2) The output desired must be clearly defined.
- 3) There is a current or anticipated shortage of experts.
- 4) The amount of effort involved can be predicted.
- 5) Resources are available.
- 6) The domain expert has sufficient time to donate.
- 7) The end users can be identified.

6.6.2 Defining Applications

The intended applications and the set of problems to be solved must be clearly identified before development. The scope of the problems should not be trivial, but should be large enough to provide a payback. However, Terry warns that selecting the most cost effective applications when first beginning an expert system program may not be wise. It would be better for an agency to start with smaller pilot projects that allow the agency to gain experience before moving to larger projects.

6.6.3 Identifying Experts

The main criteria to be considered when selecting experts are:

- 1) The candidate is, and is recognized as, an expert. Recognition among users may be important in gaining their support.
- 2) The expert must be available, and willing to spend considerable amounts of time, perhaps months, on the project. He must be dedicated to all phases of the development process.
- 3) It is also useful for the expert to be a good communicator with patience, an orderly mind, and a willingness to teach.

6.6.4 Identifying Benefits

Benefits need to be quantified in order to justify expenditures on the system. Quantifiable benefits include cost savings, time savings, increased productivity, and enhancing users' abilities to solve problems. Other benefits may exist that are not quantifiable. In order to quantify benefits, it is necessary that the intended applications are well defined, and that costs can be estimated reasonably as well.

6.6.5 Knowledge Engineering

The knowledge engineer should be proficient at computer sciences, expert systems, systems analysis and design, communication and interviewing techniques.

6.6.6 System Design and Development

Necessary steps in the design and development of expert systems include:

Problem analysis: Gathering information and interviewing experts to determine and identify the main components of the reasoning process.

Initial prototype: After initial knowledge is represented in the knowledge base, and user interfaces, explanation facilities, and other components are available, a demonstration of the initial prototype should be performed before further development.

Expanded Prototype: After the initial prototype has been extensively tested by the users and the expert, knowledge gained can be used to assess conclusions, ease of use, sufficiency of the knowledge, and other factors. Two demonstrations should be conducted during this phase.

Delivery Phase: After final changes have been thoroughly tested, the delivery system is produced. It is optimized and customized for performance, memory requirements, user interface, and other features. This may involve transfer of some or all of the modules into new computer environments.

This system allows initial requirements to be refined and changed as the system progresses.

6.6.7 Verification and Validation

Verification and validation are difficult for expert systems. If a large number of rules are used, it may be impossible to test all combinations. There are many other problems as well. These issues have not been fully addressed. Therefore it is recommended that users analyze the programs reasoning through explanation facilities and experts evaluate the programs results. Demetsky et al. (1989) and Spring (1989) further discuss expert system validation and testing.

6.6.8 Tool Selection

The appropriate expert system development tools depends on the application. Power, flexibility, ease of use, speed,

ease of prototyping, skill of the programmer, user requirements, and cost may all need to be considered. Not all expert systems tools available on the market will be useful for transportation agencies.

6.6.9 Distribution and Maintenance

Involving the user community from the start should facilitate ease of distribution. It is also desirable to avoid expert systems tools that are too exotic, or that require purchase of distribution licenses every time the system is distributed to a user in the agency.

Maintenance should be planned from the very start. The design must be as transparent and simple as possible since the designer will likely not do the maintenance. Every aspect of the program should be well documented. Version numbers should be used to keep track of updated and out-of-date copies, and a mechanism for soliciting and acting upon feedback from the users should be developed.

6.7 The Caltrans Expert System Program

In addition to the FHWA guidelines, Ritchie et al. (1988) discussed Caltrans' development of an expert system program.

Caltrans first identified potential applications of expert systems. This was done through a series of in-depth interviews with 50 top-level engineers and managers throughout the department. Figure 6.5 replicates a portion of the questions asked. A total of 45 projects were identified and

1. Could you describe the nature of the problem or task this system would address (an example may be helpful)? _____

2. Is this a current/increasing/future problem? _____

3. Should this system be PC-based? _____

4. What would be the system outputs and uses? _____

5. What would be the user inputs? _____

6a) Who would be the potential users (e.g., HQ/District/Local's)? _____

b) How many users? _____

c) Are computers available to them now? _____

d) Do they use them; if no, why? _____

7a) Would you say that there is a substantial payoff or benefit to the Department in solving this problem? _____

b) Are experts in the Department being lost due to retirements, transfers or promotions? _____

c) Are experts scarce because demand exceeds their availability? _____

d) Is expertise needed in many locations? _____

e) Is it needed in hostile, expensive or dangerous environments? _____

8a) What is the extent of algorithmic or mathematical analysis required to get a solution to this problem? _____

b) Does the problem require only cognitive, not physical skills? _____

c) Does it require expert knowledge rather than a lot of common sense to get a solution? _____

d) Do experts exist who can solve this problem? _____

e) Do they agree on the solutions? _____

f) Can they articulate and explain their solution methods? _____

g) Can they solve the problem in hours, not days or weeks? _____

h) Do they really understand the problem, or is basic research on the problem required first? _____

9a) How many experts exist to solve this problem? _____

b) Where are they? _____

c) How many are retired experts who could return as consultants? _____

Figure 6.5: Caltrans' Expert System Questionnaire
(Source: Ritchie et al. 1988)

prioritized on the basis of potential ease of implementation, potential for active support within Caltrans, and potential cost savings.

The projects were then placed in 4 implementation categories based on the assigned priorities. The categories were: 1) immediate implementation (two easier demonstration projects), 2) implementation within 1 year, 3) implementation after 1 year, and 4) future implementation.

Resources were committed immediately to the first two implementation categories. These eight projects in these two categories were consulted out to the University of California-Irvine, which is providing training to Caltrans personnel. Caltrans personnel will take over the training after 2 years, which is the expected time frame for completion of the applications in the first two categories. Projects in the second two implementation categories will be done entirely by Caltrans personnel, using experience gained from assisting the consultants.

Furthermore, a centralized knowledge engineering group was developed within the department to transfer technology, develop knowledge bases, perform quality control, and spread expert system activities throughout the department. They also specified a microcomputer environment and shells to be used. Long term training is already being considered through some workshops for the top level managers of the expert systems program.

6.8 Costs and Benefits of Expert Systems

Expert systems technologies are relatively inexpensive compared to the other advanced technologies discussed in this report. This is because little extra equipment is required, only software is needed. Simple applications can be developed using existing tools such as spreadsheets and conventional programming languages. Shells are more desirable because they allow more involved applications and are easier to use. Shells can be purchased that support all types of existing computer environments.

A few vendors were contacted to determine software prices for shells and for languages such as LISP and PROLOG that are typically used for artificial intelligence applications. Prices for LISP and PROLOG ranged from under \$100 for small microcomputer packages with limited capabilities to \$40,000 for large computer systems including installation and training. Prices for shells were in the same range, with large mainframe intelligent database systems costing as much as \$150,000 including training, installation, and customization. For some shells it is necessary to buy that particular vendor's version of LISP or PROLOG.

A knowledge engineering group will be needed to manage the technology and some training will be required, but the bulk of the costs will be accrued during system development. Development costs include system design, the knowledge engineers time, the experts time, and verification and validation time. Development costs have been reported as high as \$300,000 for complex and difficult applications, but this

is very extreme, and resulted from poor planning. They are considerably less for simpler PC based applications.

The lack of high equipment costs means that benefits from expert systems can be considerable. They allow complex time consuming tasks to be done much more quickly and can make up for a lack of experts. Quantifiable benefits include time savings, increased productivity, and enhancing the users' problem solving capabilities. There are other benefits that are harder to quantify. Paybacks for expert systems have been reported as high as 15 to 1 for business applications in some large corporations.

6.9 Implementing Expert Systems in INDOT

It should be noted that an expert system exists for estimating routine highway maintenance work loads and costs in Indiana (Tandon and Sinha 1987). Apart from this, INDOT has done little with expert systems. Expert systems is an area where INDOT can capitalize on advanced technologies and receive a high return on investment.

To reiterate what was described earlier, the use of expert systems would be beneficial to INDOT because many problems in the transportation field are so complex or poorly defined that conventional computer tools cannot be used. These problems require human judgement and expertise, which is often scarce. Consequently, expert systems have been designed to imitate the reasoning and decision-making processes of human experts. These systems are capable of explaining their reasoning process and how and why they reach certain

conclusions, just like human experts. Another benefit of expert systems is that they provide consistent and reliable results, whereas human judgement may be influenced by emotions, political factors, etc.

In order to take advantage of this technology, INDOT will need an artificial intelligence (AI) program. This can be modeled on the Caltrans program, and should include early commitment of personnel, development of a long range plan, establishment of a centralized AI management group, and initial small scale pilot projects.

A planning group will be needed to develop an initial plan. This will require detailed analysis of each functional area. The analysis can be used to:

- *Familiarize division chiefs and district managers with expert systems and gain their support.
- *Determine applications of expert systems with high potential for automation, preservation of scarce knowledge, and improved productivity.
- *Identify the nature of the applications, including existing computer environments, definition of the problem, system inputs, system outputs and uses, nature and number of users, potential benefits, and availability of experts.

This information can be used to develop a long range plan. Applications can be ranked according to potential benefits, ease of implementation, and potential for high user support. It is a good idea to start out with small scale microcomputer applications in order to prove the technology and gain experience. Microcomputer software is inexpensive, capabilities are improving rapidly, and license agreements can be reached that minimize the cost of spreading applications through the agency. One of the first tasks of the management

group or individual should be to specify a microcomputer environment for delivery of the initial systems.

Initially, INDOT may not have enough expertise to develop these systems on its own. Thus the initial pilot projects can be contracted out while agency personnel gain experience. After the completion of these projects INDOT can reevaluate the long range plan.

Eventually, a management and knowledge engineering group may be required within INDOT to transfer the technology, develop applications, and maintain quality control. The initial contracts can include training for possible members of this team. System developers must work closely with the intended user community and the experts to insure confidence in the final system. The university environment is an excellent place to make this type of arrangement.

Other states are developing a wide range of expert systems applications. These applications can be grouped into several functional areas, such as hazardous materials, roadway management, traffic operations and safety management, design, transportation planning, and highway drainage, as listed below.

Hazardous Materials Applications;

- *Characterization of hazardous waste sites
- *Hazardous waste mitigation
- *Exceptions to design standards
- *Leak detection

Roadway Management;

- *Estimation of pavement and drainage maintenance work load
- *Pavement and bridge management systems
- *Structural evaluation of pavements

Traffic Operations and Safety Management;

- *Traffic control in work zones
- *Accident analysis
- *Roadside safety
- *Analysis of roadway hazards
- *Traffic signal control
- *Installation/removal/modification of traffic signals
- *Regulation of heavy vehicles
- *Incident traffic management
- *Safety hardware advisor

Design Applications;

- *Intersection Design
- *Retaining wall rehabilitation
- *Route location selection

Transportation Planning Applications;

- *Ranking of capital improvement projects
- *Evaluation of regional transportation plans
- *State transportation improvement plans

Highway Drainage Applications;

- *Hydrologic analysis
- *Hydraulic analysis

6.10 Possible Applications of Expert Systems in INDOT

The primary objective of this section is to compile a list of possible expert systems applications and their benefits for INDOT. While this is not a comprehensive list of priority projects, it provides a possible range of expert systems that can be considered for various transportation problems in INDOT.

6.10.1 Hazardous Materials Applications

Characterization of Hazardous Waste Sites - An expert system can be developed to assist the field engineer in the characterization of a hazardous waste site, so that mitigation strategies can be implemented. The primary benefit of such a system is to minimize project delay. Other benefits include making limited expertise more readily available, acting as a

tutor for new engineers, and advising in mitigation analysis and decision-making.

Hazardous Waste Mitigation - Sites contaminated with hazardous materials must be cleaned up in the most cost-effective manner possible. An expert system can be developed to suggest a range of solutions for mitigation and remediation based on time and cost. Implementation of such a system will minimize time and cleanup costs. In addition, uniform mitigation policies and procedures will develop more quickly.

Exceptions to Design Standards - When hazardous waste sites are encountered in projects, it is often necessary to grant exceptions to AASHTO design standards. An expert system can be developed to determine whether or not exceptions should be granted, and if so, recommend strategies for cleanup, so that the need for exceptions can be eliminated. The benefits of this system would help to minimize construction delays and maximize safety.

Leak Detection - An expert system can be developed to assist the user in the investigation and cleanup procedures for leaking fuel tanks. This system would reduce the potential for groundwater contamination and minimize project delay.

6.10.2 Roadway Management

Estimation of Pavement And Drainage Maintenance Work Load - Based on observed pavement distresses and drainage conditions, the expert system will determine the appropriate maintenance activities and the expected amounts of production units and their cost (Tandon and Sinha 1987). This system

found in the estimation process and serve as a guide to the inexperienced engineer.

Pavement and Bridge Management Systems - PMS and BMS models are often too complex for the average user to understand why certain rehabilitation and repair strategies are selected. An expert system can be combined with existing PMS and BMS packages to provide explanatory information, making the system more user friendly.

Structural Evaluation of Pavements - Backcalculation of pavement layer moduli from measured surface deflections is rapidly becoming the chosen method of pavement structural evaluation (Chou and Lytton 1989). However, these backcalculations are difficult to perform; expert systems can help reduce the level of complexity involved in these computations. Furthermore, expert systems will allow a more efficient analysis of large amounts of deflection data and provide more consistent results.

6.10.3 Traffic Operations and Safety Management

Traffic Control in Work Zones - The goals for traffic control in work zones are: (1) protection of the freeway user and work force; (2) minimization of delay; and (3) efficient and economic work procedures (Faghri and Demetsky 1990). An expert system can be developed to recommend traffic control strategies based on a combination of construction controls and roadway factors. The use of expert systems would facilitate the development of consistent procedures for traffic control in work zones throughout the state.

Accident Analysis - Several agencies and researchers have performed studies investigating the causes of accidents and the strategies to minimize these hazardous conditions. However, each hazardous site possesses unique characteristics; therefore, the engineer must rely on his judgment to identify these characteristics and implement appropriate countermeasures. Expert systems can be developed to determine the most probable causes of an accident and recommend appropriate countermeasures, based on accident data. These systems would remove the uncertainty involved when dealing with qualitative information, as well as facilitate the analysis of safety issues.

Roadside Safety - To reduce the number of vehicle collisions with fixed objects adjacent to the roadway, traffic barriers have been installed to protect these objects from direct impact (Zhou and Layton 1989). However, the barriers themselves are fixed objects. As a result, the question arises of whether or not a barrier will provide adequate protection. Based on existing conditions, expert systems can assist the engineer by performing a roadside safety analysis to determine if a barrier is required.

Analysis of Roadway Hazards - Expert systems have been developed to identify roadway hazards and recommend safety improvements, based on the analysis of the roadway. The objectives of these systems are: to improve the roadway before a large number of accidents occur, to automatically analyze roadway hazards on a system-wide basis, to train inexperienced

engineers, and to provide a range of alternatives at reasonable costs (Chen and Cantilli 1989).

Traffic Signal Control - Expert systems can be implemented to improve signal control, in terms of cycle length, green phase, and phase control. The primary benefits of this system would include the following: reduction in traffic delay, improvement in energy consumption, and reduction in vehicle emissions (Ritchie et al. 1988).

Installation/Removal/Modification of Traffic Signals - Traffic control devices must follow standards described in the Manual on Uniform Traffic Control Devices (MUTCD). Based on existing traffic conditions and geometric characteristics, expert systems can recommend the appropriate course of action to follow specified by the MUTCD, i.e., whether or not a traffic control device needs to be installed, removed, or modified. Proper operation of traffic signals is crucial, since improperly operated traffic control devices can lead to unnecessary delay, reduced capacity, and safety problems.

Permitting of Heavy Vehicles - A data base can be established to store relevant information regarding regulations for vehicle weights and dimensions; an expert system can be developed to retrieve information from the data base, assess the legality of a particular vehicle, determine the permit requirements and associated fees. The development of such a system would expedite the overweight/oversize vehicle permitting process.

Incident Traffic Management - Certain procedures must be followed to advise field personnel on incident response and

traffic management decision-making when freeway incidents occur. Expert systems can be developed to train field personnel in pre-incident procedures, as well as aid in the decision-making process. The implementation of this system would minimize freeway delay and improve safety and level of service.

Safety Hardware Advisor - Several hundred details, found in specification manuals and TRB and AASHTO reports are used to choose the appropriate hardware (guardrail, barrier, etc.) for roadway safety. Human expertise plays a significant role in the decision-making process. An expert system could be developed to incorporate the various details and expertise needed to choose the necessary hardware. Thus, this information could be disseminated widely, the data base could be easily expanded and modified, and a faster response time can be achieved.

6.10.4 Design Applications

Intersection Design - The highway design process often involves tradeoffs between operational factors, such as the number of lanes, lane width, and expected traffic demand volumes. Based on budget or design constraints, expert systems can assist the engineer in the decision-making process by offering several design alternatives.

Retaining Wall Rehabilitation - Aside from the fact that many factors are involved in the design of retaining walls such as soil properties, construction material properties, cost, etc., the engineer must also consider whether or not to

replace or rehabilitate a retaining wall. Expert systems can be developed to analyze existing conditions and recommend replacement and rehabilitation strategies. These systems will remove some of the uncertainty in the design process and provide more consistent replacement and rehabilitation strategies.

Route Location Selection - The selection of the best location for a new highway project is very complex because several variables must be analyzed. An expert system could assist the engineer with the location study by evaluating different alternatives. The primary benefit of this system is a reduction in the time required to select a location; and thus, a reduction in costs.

6.10.5 Transportation Planning and Programming

Ranking of Capital Improvement Projects - An expert system can be developed to prioritize capital improvement projects, based on a weighting system of all important variables. This system could also assist in the interpretation of the results. The implementation of this expert system would aid in the long range planning of capital projects and the allocation of funds.

Evaluation of Metropolitan Transportation Plans - The review of metropolitan transportation plans is often non-uniform, due to the varying expertise of the reviewers. An interactive expert system that assists the reviewer would standardize the reviews and make them more comprehensive. The

implementation of this system would provide training in plan reviews and a more efficient review process.

State Transportation Improvement Plans (STIP) - The amount of federal funding available to a state transportation agency depends on the number of projects the agency has available for funding at a specific time. As a result, the state agency must prioritize projects to maximize the amount of federal funding. An expert system would allow the agency to examine different alternatives so that a list of projects that maximize federal funding is selected.

6.10.6 Highway Drainage Applications

Hydrologic Analysis - Many techniques are available for estimating runoff from watershed areas. None of these techniques are exact; consequently, many decisions and assumptions must be made throughout the estimation process. An expert system would suggest the level of analysis required, what data are available or need to be collected, and what techniques can be used. This system would reduce the amount of time spent on the analysis and make the results more consistent throughout the state.

Hydraulic Analysis - A considerable amount of human expertise is necessary to determine the most effective system (drainage structure, water detention system, etc.) to be used with flood control projects and watercourses transporting large volumes of water. An expert system would assist with the evaluation and selection of the most effective system, based on the risk of failure and property damage and

construction and maintenance costs. This system would automate the evaluation and selection process and provide more uniformity.

CHAPTER 7: COMPUTER TECHNOLOGY IN PLANNING AND PROGRAMMING

This chapter presents an inventory of the computer software available to and used by INDOT personnel for planning and programming. Some consideration to computer resources that would be of significant benefit to INDOT is also given. But probably the most important component of this review is an appraisal of the organizational context in which any computer models at INDOT and related agencies are used. The study team contacted all the Metropolitan Planning Organizations (MPOs) in Indiana outside of Indianapolis for information about their transportation planning computer models and the status of their transportation planning process. It is hoped that this review will form the basis for some serious discussion about the use of computer technologies in transportation planning at INDOT and throughout Indiana.

7.1 What INDOT Has

An attempt was made to contact the various divisions within INDOT where planning related computer models would most likely be found. It is likely that some models are being used by individuals that the study team was not aware of. Table 7.1 summarizes the computer models identified through a series of telephone calls and visits to INDOT. No attempt was made to list all the word processing and spreadsheet software packages in use, unless they are being used in a unique and specific application for planning or programming. Clearly, this list is

Table 7.1 A Partial List of Computer Models at INDOT

| Division | Software | Comments |
|--------------------------------|---|---|
| Opns. Spt. | QUEWZ | Work zone mgt. |
| Prog. Devel. (Envir. Svcs.) | MOBILE 4 HEP STAMINA WET CALINE | Air pollution Habitat Evaluation Procedure wildlife impacts Noise impacts, barrier design Wetlands evaluation from Corps of Engrs. Air quality; no PC version at INDOT yet |
| Prog. Devel. (Hwy. Stats.) | --- --- | Spreadsheet: ADT forecasts Count station and veh. classif. telemetry |
| Prof. Devel. (Prelim. Eng.) | RDS | Outdated; being replaced by CAD |
| Prog. Devel. (Urb. Prog.) | QRS II HCS --- | Used on occasion Not used yet Spreadsheet: implem. pop.-based funding formula |
| Public Trans- portation | --- --- --- --- | Spreadsheets: PTO reports Spreadsheet: Sec. 18 alloc. Spreadsheet: Ride check form Spreadsheet: Sched. timetable COMSIS cost alloc. model |
| Tp. Planning | QRS II | Not used yet |
| Policy & Budget | INDOTREV | Highway revenue forecasting |

far from exhaustive, but it gives an idea of the nature of computer model use at INDOT.

The Public Transportation Division illustrates how the mission of an agency, not the particular mode, determines the appropriate software models to be used. There is no need for that division to use the kind of models that a local transit agency might find helpful: run cutting, route- or network-level demand models, etc. Instead, that division has developed several in-house spreadsheet-based programs to manage data reported by the Public Transit Operators (PTOs) and to provide some decision support tools to the PTOs. However, some of the software used by the Public Transportation Division to evaluate data sent in by PTOs can also be used by the PTOs to evaluate service changes. The Public Transportation Division has assisted New Castle and Richmond in this way.

The Transportation Planning Division is currently considering the issue of appropriate direction and level of detail for its future computer modeling efforts. This is addressed further in Section 7.3.

It was not until recently that software designed for environmental analysis could be run on microcomputers. By then, most MPOs had gotten into the practice of letting the State do such computer analysis. Considering the variety of problems in the environmental area -- air quality, water quality, wetlands, habitat preservation, noise impacts and barrier design, and so on -- it may not be a bad idea to maintain some centralized expertise, control, and oversight,

even if MPOs choose to acquire software for these purposes.

7.2 What the MPOs Have

A telephone survey was conducted to determine which software related to transportation planning each MPO had and the extent to which it is being used. In addition, a brief conversation about the status of the planning process at each MPO took place, and some ideas about the use of computer technologies emerged. The survey was confined to the use of computer models for travel demand modeling (TDM), traffic impact analysis (TIA), and environmental analyses (ENV). A summary of the MPO computer model inventory is given in Table 7.2. The list may not be exhaustive, but it gives a fairly good idea of the status of travel demand modeling at the MPO level in Indiana. No programming activity in the usual sense is undertaken at the MPO level.

The pattern is obvious: The smaller MPOs appreciate the low purchase price and reduced data requirements of QRS II, while the larger MPOs feel the need for a more powerful and flexible software. The MPOs using MINUTP have each other and an active consultant as a source of technical assistance. At the time the survey was conducted, NIRPC was converting to EMME/2 with the assistance of the Chicago Area Transportation Study (CATS).

7.3 What INDOT Needs

Perhaps because its results are not immediately visible in "concrete" form, the role of transportation planning is

Table 7.2 Computer Models at the MPO's in Indiana

| Area | Purpose | Software | Comments |
|-------------|-------------------|----------------------|---|
| Anderson | TDM Misc. | QRS II MicroTRANS | Calib. is slow Land use est., Traffic Growth rates |
| Bloomington | TDM TIA | QRS II | Not used yet by Engr. Dept. |
| Evansville | TDM Air | MINUTP MOBILE 4 | Calib. by consultant from EPA |
| Fort Wayne | TDM TIA Air | MINUTP HCS --- | QRS II not adequate Intersection and corridor analyses Not used yet |
| Kokomo | TDM | QRS "I" | Need to update software |
| Lafayette | TDM ENV | QRS II | Calib. has been slow by consultants |
| Muncie | TDM | QRS II | Being set up |
| NIRPC | TDM Misc. | EMME/2 QRS II | Convers. from TRANPLAN Corrid. study |
| South Bend | TDM | MINUTP | Had difficulty in QRS II |
| Terre Haute | TDM TIA | MINUTP | By consultant By city engr. |

often underappreciated. Given adequate resources to devote to training, data collection, and model acquisition, development, maintenance, the INDOT planning effort will provide valuable information for problem identification, policy development, and priority-setting. The additional investment will be modest, but the payoffs promise to be significant.

The alternate ways in which those additional resources are invested must be carefully evaluated. The Transportation Planning Division, for example, is considering questions such as the following.

- Is there a need to establish a strong in-house travel demand modeling capability?
- If so, at what level of detail?
- For what size study areas?
- For what modes?
- Who would be the "consumers" of the modeling effort's results?

A better initial direction might be to become a central clearinghouse for data of use to other INDOT divisions and the MPOs. HPMS data have some inaccuracies and, because they are a sample of the highway network, have enormous gaps that must be filled before it becomes a comprehensive data base. An obvious next step is to acquire Geographic Information System (GIS) software for this data clearinghouse function. Although GIS is discussed in Chapter 4, that its value is already being exploited for planning, programming and other purposes by other states must be mentioned here. The INDOT Highway Statistics Section's road inventory system needs to be

connected to the proposed GIS. The resulting improved data retrieval capability and the ability to highlight certain elements of the highway system by user-specified characteristics will be major benefits of the conversion to GIS.

While detailed urban passenger travel demand modeling can be left to the MPOs, there are other planning activities that are probably best carried out at the state level. These include various management systems including pavement and bridge systems, freight transportation modeling, and air travel analysis. These activities probably ought to remain at their current locations within INDOT, but have their data centralized and coordinated.

At present, the Preliminary Engineering Section has difficulty in generating the topographic data it needs. Contours, soil conditions, etc. must be transferred from maps and paper reports, when automated access to basic survey and soil data could substantially improve the productivity of the INDOT personnel and the quality of their analyses. As Table 7.1 has already noted, the RDS (Roadway Design System) software is unwieldy and outdated. The Preliminary Engineering personnel look forward to a CAD system scheduled to replace it in the near future.

Current procedures for collection of condition data have unavoidable drawbacks. Distress data by visual observation is subject to variations between individual observers. Automated procedures ought to be explored. The use of image processing, infrared photography, and GPS (global positioning systems) are

technologies ripe for investigation. Once the data are collected, they must be easily accessed by the various divisions and districts. The concept of an integrated data base now being pursued by the Information Services Division will make this possible.

The Environmental Services Section of the Program Development Division carries out most of the environmental analyses beyond the vehicle emissions estimates made by some travel demand software. However, even at INDOT, some of the analyses are done by hand. Highway pollution runoff estimates are now done by hand, following a procedure outlined in an EPA manual. Likewise, groundwater analysis is conducted without software that would improve the productivity of the INDOT personnel involved. The air quality package CALINE still resides on the mainframe computer, whereas the PC version is available and would be a more useful tool. The Environmental Services Section needs the capability to access data on wetlands, woodlands, wildlife habitat, etc. and to combine the information in a systematic manner for the environmental assessment of various projects.

While the number of software packages for many planning and programming functions continue to increase, some activities have not yet been reduced to an "off-the-shelf" computer model. An example is freight transportation, especially intermodal freight transportation. To date, such models have had to be "custom-built". Certain planning principles and relationships can be transferred to these models, but specific features must account for the data that

are (or are not) available, the level of detail desired, and the particular policy and/or design issues being addressed. INDOT is currently considering a research initiative in this area. Because the data problem is so important to this modeling effort, new technologies can be a great help. Weigh-in-Motion, Automated Vehicle Identification, and Automatic Vision and Image Processing are being tried in several states. Their potential for strengthening what is usually the weakest link in the freight transportation modeling process is enormous.

Research efforts in other states should be monitored. In some cases, INDOT could borrow and adapt ideas that were successfully applied elsewhere at considerable savings in time and investment, when compared to independent research efforts or waiting for a commercial product. An example is technologies such as expert systems applied to the issuance of overweight permits to truckers. Several states, including Minnesota and Texas, have undertaken projects on this topic.

7.4 Recommendations for INDOT

This section contains some ideas on how INDOT might be able to better perform its mission by providing some assistance to the MPOs in the area of computer modeling. The variation among MPOs, in terms of philosophy, personalities, historical relationships with INDOT, and particular MPO needs, make any blanket recommendation a risky one. Nevertheless, there are some common items that deserve consideration.

1. Leadership. There are several possible ways in which

INDOT can become a leader in the field of transportation planning in Indiana. In Alabama, Florida, Kansas, Kentucky, Michigan, and Texas, the state DOT played an important role, if not a dominant role, in seeking/suggesting/prescribing a particular software package for use by the MPOs in its state. This strategy, if possible and if properly implemented, offers uniformity in modeling procedures and facilitates the transfer of data and technical expertise. As years go by, this strategy will become increasingly difficult to accomplish. In Indiana, the larger MPOs have already made choices of software for transportation planning, usually choices that conflict with the preferences expressed by smaller MPOs. It may not be wise to impose the same software on metropolitan areas that can be so different in size, configuration, and location. Instead, leadership can be exercised in helping the MPOs meet some the needs listed below.

2. Training. It is quite common for the computer model users at the MPOs to have an educational background that did not include transportation planning as a formal subject. These users must learn on the job and, if they are fortunate enough to be given the time and funding, by attending conferences and short courses. Another problem is the high turnover in transportation planners experienced by many MPOs. It has been difficult to hire trained planners, or train those hired to fill the planning positions, then retain them once they are trained. Some actions can be taken to upgrade the expertise with which the travel demand computer models are used.

a. To provide the formal background in transportation

planning, appropriate planning courses offered on TV at various universities can be considered. Alternative or supplementary instruction could be offered by HERPACC in cooperation with the MPOs' organization. There are also some NHI short courses on the use of specific software packages.

- b. To provide a clear and up-to-date familiarity with INDOT policies and procedures in transportation planning, a periodic workshop could be conducted by the Transportation Planning and Program Development Divisions. Perhaps this workshop would include specific sessions on computer models or reserve time for computer model "user groups" to share experiences and techniques.

3. Cooperation/Coordination/Continuity.

- a. Data.

Even if an MPO has a modern software package and competent modelers, there is still the problem of an aging data base. Few urban areas or states have origin-destination data that are less than ten years old, and many are much older. Even link volume counts are not as complete, accurate, or available as they should be.

Most MPOs are willing to be part of a coordinated program to collect and share data in a convenient form. Either the Program Development Division or the Transportation Planning Division is eager to fill in the gaps in HPMS and other data bases, so that its planning and programming efforts of the future build on a sound

foundation. Some agency needs to take the lead in proposing what data needs to be collected and in what format. The resulting data should be easily transferable by electronic means in a form that is, if not immediately usable, at least easily convertible by the end-user.

For example, accident data are now collected by most MPOs via paper reports obtained from local law enforcement agencies. Accident data received from the state often (i) are too voluminous, (ii) are in a format incompatible with MPO hardware or software, (iii) contain information that is unintelligible to the MPO. A particular problem is the use of "pseudocodes" to identify accident locations. Approximately twenty years ago, a study for the Indiana State Highway Commission recommended a switch to use of latitude and longitude as reference points for locating accident sites. The use of latitude and longitude also is compatible with the inevitable conversion of many data bases to Geographic Information System (GIS) packages. The "clean-up" of accident reports into verified content and standardized format could be overseen by MPOs. Then electronic data transfer could be accomplished using ASCII file format.

It should be mentioned that the Transportation Planning Division has already arranged with the MPOs to obtain the 1990 Census Transportation data. This is a welcome precedent for future cooperative ventures to the mutual benefit of both groups.

b. Coordination within INDOT.

Currently, most MPOs have their greatest contact with INDOT through the Urban Programming Section of the Program Development Division, and for some MPOs, that contact is not very frequent. As INDOT seeks new ways of accomplishing its mission, the computer modeling element could be a means by which the Program Development Division and the Transportation Planning Division develop a closer working relationship. The two divisions share common interests in data collection, computer models, and the activities of the MPOs.

c. Corridor analysis beyond an MPO's jurisdiction.

This situation may call for INDOT participation. The involvement may be as facilitator and coordinator, or it could require a significant modeling effort in the absence of others who are capable.

d. Environmental Analyses.

As mentioned earlier, software for environmental analysis has so far been primarily held and used at INDOT. With the increasing concerns regarding environmental aspects of transportation and with the growing transportation planning requirements set by Clean Air Amendments of 1990 and Intermodal Surface Transportation Efficiency Act of 1991, it is imperative that local planning agencies have the capability of environmental analyses within their jurisdictions. However, INDOT can take an active leadership role in training the local planners and coordinating the local efforts.



CHAPTER 8: QUALITY ASSURANCE IN CONSTRUCTION

Although there are many tasks that are part of construction inspection, one important task involves the monitoring of the construction process to determine on whether the procedures, labor, materials, safety, and equipment are in compliance with the project's plans, specifications, and contract. From this monitoring, the work is either accepted or rejected; the work that is acceptable may not exactly comply with the specifications but may fall within tolerance limits set by the plans and specifications. Although deviations in the tolerance limits may be accepted and payment for the work would not be affected, certain deviations in the work could have adverse effects on the performance and longevity of the work. Quality assurance can be defined as the necessary planned and systematic actions to assure that a final product of a given task(s) will perform its intended function. Hence, quality assurance is a management tool. Quality control, on the other hand, is a production tool since it deals with the actions involving the physical materials, processes, and services which provide a means to determine and control given characteristics to standardized criteria. Both quality assurance and quality control are combined together to form a quality assurance program which formally outlines the policies, procedures, and practices to meet quality requirements and associated contract requirements (ACI 1990).

In this chapter, advanced technologies for quality assurance in highway construction will be discussed as well as a quality assurance program presently initiated by the Indiana Department of Transportation (INDOT). The potential for automation and integration into INDOT's automated construction data management system will also be investigated.

8.1 INDOT's Quality Assurance Program

INDOT currently has a quality assurance program for the construction and reconstruction of pavements. The need for this program was primarily influenced by the variation in quality of pavement materials. Closer control was needed to get pavement materials and their associated characteristics away from the extreme tolerance limits.

The quality assurance program for bituminous pavements began approximately four years ago and is now part of INDOT's supplemental specifications (INDOT 1988). In addition to specifying the requirements for the job mix formula, the quality assurance specifications include tolerance limits for the range of gradation, the range of bitumen content, the range for sieve size, the crushed content, and the in-place pavement density. These tolerance limits are particular in that adjustment points are correlated to them. These adjustment points are then added together for a given pavement section and then subtracted from the value of 100. The resulting value would represent the percentage of payment directed toward the contractor for the work performed. Because of this potential decrease in payment, there is an

incentive for the contractor to provide consistent, high quality material.

A similar quality assurance program for portland cement concrete was started two years ago and is part of INDOT's Special Provisions (INDOT 1990). The periodic, regular testing will involve the following concrete properties: flexural strength, air content, unit weight, water/cement ratio, gradation verification, and pavement smoothness. Price adjustments, if necessary, will be made for flexural strength, air content, and for pavement smoothness.

Up to the present time, INDOT has been applying the two quality assurance programs on selected pavement projects throughout the state. Feedback from field staff and contractors have been favorable. Furthermore, INDOT has plans to enact additional quality assurance programs involving structural portland cement concrete and the material and density requirements for aggregates.

8.2 Quality Assurance Activities Outside of Indiana

At the present time, many states are developing construction data management systems. While these uniquely tailored systems can vary significantly from state to state, attention is being given to material testing and varieties of quality assurance/control. Since many construction data management systems are currently in the planning or development phase, it currently is not clear on how all state DOTs will develop a QA program and what will be the specific scope of these programs. A number of recent efforts in this

area are discussed below to present the nature of these programs.

The Oklahoma DOT (ODOT) has developed a quality assurance-quality control (QA-QC) program which is very similar to the INDOT program (Hughes and Ahmed 1990). Three special provisions were developed for asphalt concrete pavement, portland cement concrete pavement, and structural concrete pavement. ODOT is currently reviewing the special provisions for two other areas, embankments and bases. Under this QA-QC program, the contractor is responsible for quality control of processes whereas ODOT is responsible for the assurance and acceptance of the finished product. Oklahoma's basic concepts of sampling, testing, and determining payment factors for bituminous and portland cement concretes patterned INDOT's methods. ODOT has been putting effort into its training program for QA-QC although there has not been mention of advanced technologies. Other states such as Ohio and Minnesota currently have quality management programs which place an emphasize on turning the responsibility of the field quality control over to the contractor (Holt 1990).

The Virginia DOT (VADOT) redesigned its Contract Quality Assurance Program in 1987 which established three levels of construction control. First, the contractors are the responsible party for the oversight and quality control of the project with respect to the specifications. Second, VADOT is responsible for quality acceptance of the project and accepting or rejecting the given work. Third, VADOT is responsible for determining new methods for construction

inspection when it is necessary to ensure desirable project quality control. In this system, VADOT is attempting to include as much of the construction inspection procedures as possible and has classified 1800 tasks under 75 categories. What results is a checklist weighted for the benefit of important tasks. The use of automated clipboards interfacing with a construction data management system was being considered for this task. Adjustments to quantities or pay items are not incorporated but such a system may be used against a contractor with poor performance for pre-qualification to bid on other construction projects (Lynn 1989).

8.3 Quality Assurance Automation

Given a procedure which has been standardized, computerized automation can be applied to enable rapid data accumulation and transfer. In regards to INDOT, a limited automated version of its bituminous quality assurance program is currently in operation. This application was developed in-house in 1991 by the Crawfordsville District. At the present time, Crawfordsville has been the only INDOT district to use this program. The program runs on LOTUS 123 software and can be used on portable lap-top personal computers. The use of this program is primarily for INDOT technicians performing extraction tests at the asphalt plant. For each test, the technician enters in three types of data. The first is the sample data. This data would include the date, time, lot number, test number, sample weight, tare weight, filter

weight, celite weight, fines correction factor, and the weights for aggregate, filter, and celite after extraction. The next type would be the sieve data and would simply involve the weight retained on each sieve during the sieve analysis. The last data type would be the crush data and would include the weight picked for the crush count. The technician will enter in the data for four tests for the given lot. Then the program calculates and compares the averaged data to the job mix formula, which is also on file, and the acceptable tolerance limits for sieve size, bitumen content, combination of sieve size and bitumen content, and the crushed content. If any of the calculated parameters are found to be outside of the designated tolerance limits, the program will assign the appropriate adjustment points to the lot. Lastly, all of the individual adjustment points will be summed to represent the adjustment factor for that individual lot. This information is then forwarded to the project engineer for the determination of the monthly cost estimate. The adjusted points for pavement density was not included in the program since that task is performed by construction inspection personnel and not by material testing personnel.

Although this application is limited, it shows potential for the expansion of the QA program throughout the state as well as into QA programs for other items (PCC, aggregates, etc.). The automation of QA programs should be therefore considered within the overall context of construction data management systems.

8.4 INDOT's Automated Construction Data Management System

INDOT is currently formulating an automated construction data management system. This system would be comprised of personal computers in the field offices, a mini system in the district office, and a main frame computer system in the central office (McCullough 1991). In essence, data entry will occur at the field PC, then transferred to the district hardware for storage and further processing, then later transferred to the main frame in the central office for storage and accessibility from other systems. The development of this system has been hindered by the recent state budget shortfall so a contingency plan is now under way. Under the contingency plan, the short term approach is to utilize the existing PARADOX based construction records program operating on certain projects. This program will be expanded and enhanced to perform the features that are of interest to INDOT. These features would include: a bid analysis management system (BAMS) tie-in, computerized specifications, user ease, localized computing capability, and the ability to use portable data collectors, asphalt/concrete plant tie-in, bar codes, lab equipment interface, electronic signatures, document scanner, and electronic clipboard capability. The long term approach may involve further development of the short term approach or could be changed by means of switching to a higher level computer language.

8.5 Integration

Since INDOT is currently developing its short term

contingency plan for its automated construction data management system, it is not possible to accurately describe on how an automated quality assurance is to be implemented within the larger system. But the potential for such integration is great when considering the benefits. Quality assurance basically assists the Materials and Testing and the Operations Support Divisions in determining the quality of the materials and work provided by the contractor. Integration within a larger construction management system would increase the effectiveness of quality assurance by providing relevant information to field and head office personnel on a rapid, easy-access basis. The portable lap-top PCs used by field technicians can transfer information via telephone modem to the district/main office. In addition, testing information can be readily and easily updated when additional tests results are known. For example, portland cement concrete flexural beam breaks cannot be made the same day that the pavement subplot is placed. These beam breaks will be performed after a cure time of either 7, 14, or 28 days. With proper integration, the test results can be known immediately by the project engineer, contractor, and personnel within the Materials and Testing Division. The current automated quality assurance program could be implemented within INDOT's exiting construction managment data system at this time since INDOT's PARADOX software has the ability to convert the LOTUS language into useable version of PARADOX.

8.6 Costs and Benefits

The cost of development will be influenced by hardware, software, communication, hardware maintenance, information services staff support, and training. To begin with, the hardware will most likely be the most expensive item for automating the quality assurance program. Each quality assurance construction project would require at least one lap-top PC-AT (286 machine), a printer, and a modem. A typical cost for this hardware setup would be approximately \$3000. However, this cost could be reduced if items such as the printer and modem are already provided for the construction engineer's data management PC work station. The sharing of common hardware and support accessories between the construction engineer and the quality assurance technician would reduce costs as well as complement system integration. Secondly, the current software was basically developed in-house in the Crawfordsville District. Although other options for software development exist, including consultant development, a combination between in-house and consultant development, the in-house development would likely be the most cost effective. The automated quality assurance program for bituminous pavements was developed at Crawfordsville by using a standard LOTUS spreadsheet format. There was no formally budgeted time for its development. Because of this, it is not possible to provide an estimate of in-house development cost. However, as shown with the Crawfordsville case, the in-house development time and cost should not be discouragingly high. There will be a cost to equip the lap-top computer with local

computing capability. The cost of obtaining software, such as spreadsheet, database, engineering calculations, etc., and their associated licenses should approximately be \$700 per lap-top PC. Thirdly, communication or transferring data from the field to the district/central offices will depend on frequency, duration, and transmission distance. Two basic options are available: business telephone line with modem or a dedicated data line. With a business line and modem, a typical installation fee is \$100 with a monthly toll call rate of approximately \$50 per month. A dedicated data line will be more expensive: a \$720 installation fee and a \$450 monthly service. As stated previously, the communication costs could be reduced simply because of the shared use between the field testing technician and the construction engineer. Lastly, additional costs for support staff and training can be anticipated. An information services support staff can consist of existing personnel within the Materials and Testing Division working on a part-time basis. This staff would maintain, service, and update the quality assurance programs. Training field technicians on the quality assurance programs could be performed through short courses, workshops and instructional booklets. In fact, the Crawfordsville District has developed a user's manual to assist its field technicians to use properly the quality assurance program.

The automated quality assurance program can be a powerful and time-saving tool for INDOT's field personnel. The automated program is consistently accurate since it eliminates any calculation errors that could be made by the testing

technician. It will also be able to save field technicians' time. According to the personnel in the Crawfordsville District, the current automated program saves technicians approximately 15 minutes per test when compared to the manual method. Although this time savings can be regarded as a return on the investment of automation, it also can assist in improving quality. Because the field technician knows the test results sooner, the sooner the technician can relate this information to the contractor so that changes can be made before additional lots and sublots can be placed. Therefore, the automated quality assurance program will provide timely information in regards to the quality of the construction material and changes, if necessary, can be performed more readily thus assuring the overall value of the construction project. Consequently, it would be highly desirable to expand the automated quality assurance program into the other INDOT districts.

8.7 Recommendations for INDOT

An effective quality assurance program will be beneficial to the goal of high quality roadway construction. Both INDOT and contractors will realize the usefulness of this program by detecting variations in material properties rapidly before much of the subject material has been committed to the project. A fully automated quality assurance program, integrated with a much larger construction management system, will increase the speed and quality of communication between field personnel, relevant district/main offices, and the

contractor.

The discussion in this chapter involved quality assurance within the constraints of current contracting practices. However, it is important to indicate that the recent experience of highway agencies in many European countries has proved that when the responsibility for the quality of construction is left directly with the contractor, the overall results are significantly better. If the contracting practice is such that a required level of performance is guaranteed by a contractor over a specified service life of a facility, the task of selecting an appropriate contractor involves identifying the contractor who can provide the desired level of performance at the least life cycle cost. The contractor can then be free to use innovation in the use of materials and construction practices in order to provide the expected performance level at the least cost.

The use of computer technologies can significantly assist in the development of appropriate quality performance measures and associated life cycle cost analyses so that innovative contracting practices can be fostered to provide a higher level of service to road users.

CHAPTER 9: ROBOTICS AND AUTOMATION

Roadway construction and maintenance activities consist of operations that are highly labor intensive. Many of these activities have components are also repetitive in nature. The productivity of these activities can be greatly improved by the use of robotic automation. First applied in the manufacturing field, robotic machines have automated various assembly line tasks. There has also been recent robotic applications in the building construction industry. Automated highway construction and maintenance equipment have the potential to reduce labor requirements, increase worker safety, and improve work quality and productivity. In this chapter, the possible application of automated robotics in highway construction and maintenance is discussed.

9.1 Levels of Work Automation

Roadway construction and maintenance equipment can be grouped into three basic categories (Skibniewski and Hendrickson 1990). The first category is mechanized equipment which basically has been in use for most of the twentieth century. Mechanized equipment induces large forces through the use of hydraulic and transmission hardware for various work tasks. The second category is numerically controlled equipment. This type of equipment has the capability of

performing repetitive, large-volume tasks with little or no operator assistance. However, numerically controlled equipment require a working environment that is constant in nature. Any obstacle in the working environment which could disrupt the continuous execution of work tasks will warrant removal by the operator. The last category is for autonomous equipment. The robotic nature of the equipment enables the independent execution of one or a variety of tasks. The independency of the execution can either be partial or full depending on the degree of automation. Equipment operation is actuated by the use of sensory data obtained from the environment. These sensory data are processed by the automated equipment to actuate relevant machine actions. Therefore, unlike their numerically controlled counterparts, automated machines may have the capacity to react prudently to unforeseen work site conditions.

9.2 Basic Components of Robots

There are five basic technological components which form a basis for development of automated road construction and maintenance machines (Hendrickson and Au 1989; Najafi and Naik 1989). The first component involves manipulation; robots generally are equipped with an arm that enables the ability to grasp an object and move it from one location to another. Manipulator arms typically have six axes of motion: three translational (left-right, up-down, forward-backward) and three rotational (pitch, roll, yaw). The second component consists of end-effectors or devices that enable the robot to

do any specific task. End-effectors are usually mounted on manipulators. For automated highway construction and maintenance equipment, typical end-effectors could consist of scrapers, sprayers, discharge nozzles, and sensors. Mobility systems are the third component and are necessary to transport the robot throughout the work site. Such motion systems exist to some extent in the automated factory environment. However, such systems will need to be modified in order to compensate for the increased locomotion requirements in the roadway construction environment. The fourth component involves the use of controllers designed to control and coordinate the motion and position of manipulators and end-effectors. The controller is equipped with software to enable a machine operator to record a sequence of manipulator motions and to play back these particular motions a desired number of times. The last component covers the utilization of sensors which convert environmental stimuli (touch, sound, sight, etc.) into electronic signals. These signals will then be recognized and acted upon by the controller units of a given robot.

9.3 Numerically Controlled Equipment

Examples of existing roadway equipment designed for the performance of repetitive construction and maintenance tasks are discussed in this section. These examples are not equipped with sensors and require actions based on external environmental stimuli from the machine operator (Skibniewski and Hendrickson 1989). Hence, considerable amounts of site preparation are necessary prior to the execution of work

tasks.

A multi-purpose traveling vehicle has been developed by Societe Nicolas of France (Point 1988) to be used for a variety of road maintenance tasks. The principal purpose of this vehicle is for the mowing of grass around roadway curbs. Compared with traditional equipment methods, it has been claimed that the automated vehicle can save up to 50% of mowing costs. The vehicle is equipped with a variable height suspension for loading and unloading items such as pallets. The present total cost of this vehicle is approximately \$270,000. The multipurpose vehicle is planned for future tasks including sowing, ditch excavation, road marking and cleaning, surface cutting, brushwood cleaning, and salt dispensing.

Four automated portland cement concrete slipform machines have been developed by Miller Formless Systems Company (Skibniewski and Hendrickson 1990). Each slipform machine differs in size and capability with the two smallest machines suitable for curb and gutter and standard sidewalks. The second smallest machine is a sidemount unit capable of slipforming retaining, median and parapet walls. The two larger units are designed for large-volume work such as pavements. All of the slipform machines operate on a play back mode basis while following a predetermined and precleared path of work. In addition, these machines are able to place concrete closer to obstacles than with alternative forming methods. Because these units have lower labor requirements, the cost savings potential with respect to traditional forming

methods is apparent.

The French company Secmar (Point 1988) has produced a prototype for an integrated surface patcher. The principal uses for this surface patcher include hot surface repairs (surface cutting, blowing, tack coating with emulsion, etc.), and repairs continuously requiring treated and untreated granular materials. The surface patcher is also suitable for repairs using aggregate/bitumen mixes, cement-bound granular materials, untreated well-graded aggregates, and granulates used for the sealing for wearing courses. Despite its versatility, the integrated surface patcher is not capable of surface shaping and pothole filling. In addition, the machine is numerically controlled and does not have the ability to make decisions with regard to un-predetermined tasks. It is primarily used for routine maintenance tasks. It has been claimed that the integrated surface patcher can yield overall cost savings of 40% when compared with traditional equipment and methods.

9.4 Autonomous Equipment

A number of automated prototypes have been developed that have successfully integrated manipulator and end-effector tool action with environmental information provided by sensors. Examples of these applications (Skibniewski and Hendrickson 1989), in addition to prototypes currently being developed, are covered in this section.

A laser-guided, micro-processor controlled grading machine has been developed by Spectra-Physics of Ohio

(Skibniewski and Hendrickson 1990). A laser transmitter produces a horizontal plane of light over the job site. The laser is picked up by receivers mounted on the grading equipment. The height of the grading blade with respect to the laser light is measured. This information is relayed to the microcomputer where adjustments to the blade height can be made by means of electrically activated valves installed in the grading machine's hydraulic system. The key advantage of this automation is the increased productivity, speed, and quality of grading; the machine operator is relieved of having to manually control and position the grading blades.

The U.S. Air Force in cooperation with the John Deere Company has developed an excavator to be used in the Air Force's Rapid Runway Repair (RRR) project (Bode 1984). The primary task for the excavator is the repair of runways damaged during bombing raids. With this automated system the Air Force hopes to remove humans from life threatening work environment during combat situations. The Air Force is also studying the potential of using the excavator in other tasks such as heavy construction work, combat earth moving in front-line areas, mine field clearing, and hazardous material handling. These developments can assist in the deployment of robots to perform tasks such as the repair of high volume road sections, the cleaning of hazardous spills, and so on. Recently, Carnegie-Mellon University (CMU) has produced a prototype of a robotic excavator (REX). REX utilizes a sensor-built surface model to plan its digging action and interprets sonar data to build accurate surface and buried

object depth maps to model the excavation site. Based on the surface topography and the presence and location buried obstacles, appropriate trajectories are generated and executed.

SHRP has developed a prototype field system to demonstrate the identification, mapping and tracking of routed pavement cracks. Once cracks are identified and mapped, specialized control software is used to traverse cracks on the pavement surface for cleaning and filling.

The Kajima Company of Japan has developed an automated machine mounted on a computer-controlled mobile platform and equipped with mechanical trowels that produce a smooth, flat surface. With the use of a gyrocompass and a linear distance sensor, the slab finishing machine navigates itself and automatically corrects any deviation from its prescheduled path. Finishing cast-in-place portland cement concrete slabs is a arduous, laborious task; the slab finishing robot is designed to replace at least six skilled workers (Skibniewski and Hendrickson 1990).

The agency survey conducted in the present study indicated that the California Department of Transportation (CALTRANS) is currently developing several autonomous machines for maintenance purposes. All automated projects are conceptual in nature and that "proof of concept" testing would accompany each development. The first autonomous project was applied toward the placement of pavement markers. The second application involves automated crack sealing. The equipment is currently being developed with the prototype completed in

1992. The third project, scheduled to be delivered in 1992, focuses on the automation of litter retrieval. Lastly, CALTRANS is currently developing an automated roadway paint striper. The equipment for data acquisition and sensory feedback system was to be developed between 1990 and 1991. The testing of an automated guidance and control system was to take place in 1992.

The Minnesota Department of Transportation (MNDOT) has also investigated the feasibility of using automation devices in its operation. An example is the installation of a remote control device within maintenance trucks. The remote controlled truck would be used to increase work zone safety and productivity. Advanced research on automated roadway navigation has been performed at Carnegie Mellon University's Robotics Institute for some time. The CMU Robotics Institute has developed automated vehicles capable of road following based on visual information provided by sensors such as television cameras, radar, ultrasound emitters, light-emitting diodes, and infrared scanners (Dowling et al. 1987; Thorpe and Kanade 1988).

9.5 Automated Pavement and Bridge Inspection

Despite the fact that the number of commercially available automated inspection technologies for pavements and bridges has multiplied over the last few years, their use by highway agencies in the nation has been slow. The major reason for this has been the difficulty in demonstrating the benefits of automated technologies in reducing the long-term

costs of maintaining systems of infrastructure facilities. These potential benefits may be realized as a result of:

- * increased speed of data collection, which may allow highway agencies to obtain up-to-date information on the entire network of highways on a regular basis at low costs;
- * consistency of the information of pavement condition, through automated interpretation of pavement images, which may eliminate the subjectivity involved in human inspections;
- * early detection of underlying loss of structural integrity for pavements and bridges, which may allow the responsible agency to take early, inexpensive repair activities instead of the major rehabilitation or replacement activities which would be necessary in later stages of the life of that facility.

For INDOT, as for other transportation agencies, it is necessary that these potential benefits be demonstrated before an expensive technology adaptation effort is started. A rigorous evaluation of the costs and benefits of different automated inspection tools for highway pavements and bridges is therefore required.

Such an evaluation should consist of the following elements:

- * analysis of the accuracies and precisions of the different inspection technologies available (the major classes of technologies are photographic and video

imagery for surface distress and ground penetrating radar and infrared thermography for sub-surface defects for both pavements and bridge decks); this analysis should be based on actual field testing and thorough statistical analyses;

- * quantification of the costs and benefits associated with the accuracies, precisions, speeds and other parameters of these technologies;

- * economic cost/benefit analysis of the different technologies, based on the results of the above-mentioned analyses.

The first element of the evaluation is critical because, as demonstrated in Humplick (1992), there may be large inherent biases and random errors in inspection technologies. Such errors have important implications on the life cycle costs of transportation infrastructure facilities, as demonstrated in Ben-Akiva et al. (1991) and Madanat (1992), because incorrect condition information about a highway or bridge may lead to incorrect maintenance and rehabilitation decisions by the agency in charge of that facility. Therefore, it is critical that a comprehensive evaluation, along the above-mentioned lines, be undertaken by INDOT prior to adopting any automated technology.

9.6 Costs and Benefits

The predictability of automated system costs is relatively low. Robotic applications in industrial

manufacturing as well as controlled-environment laboratory testing have not yielded costs which can be directly applied to the construction work site. Furthermore, the costs and performance of such robotic components as sensors and work manipulators can not be forecasted with a degree of accuracy due to the lack of relevant design experience and performance of prototypes (Skibniewski 1988).

Automated system costs can be divided into two major groups. The first group involves research and development. The modifying and upgrading of existing industrial robotic components in order to meet the demands of the construction work site environment will take up a major part of the total research and development cost. Also, costs associated with the development of prototypical robotic components will be evident. Lastly, the development of software to operate robotic and automated systems can represent a substantial investment.

The second major group of system costs will include operating costs. These costs will be highly dependent on the characteristics of the robotic hardware as well as associated maintenance. Also included would be the appropriate labor costs, system set-up and dismantling, and robot transportation costs.

The principal benefits of automated roadway construction and maintenance work involve quality of work, time saving, worker safety, and labor saving. Robotic applications can perform repetitive tasks on a continuous basis; automation insures the quality and accuracy of the tasks involved.

Secondly, construction or service time can be reduced since the robotic application can be programmed in a time efficient manner. In addition, automated machines will not experience the physical fatigue which can hinder the production process in a manual, non-automated environment. Thirdly, automated robotic applications are well suited to tasks and/or environments that are hazardous in nature to human workers. Lastly, labor requirements can be reduced in certain work tasks where robotic applications have replaced manual labor. Likewise, potential labor shortages in specific tasks (concrete finishing, sand blasting, etc.) can be met with automated work applications.

9.7 Recommendations for INDOT

Automation of appropriate roadway construction and maintenance activities holds much promise. It is clear that if applied effectively, automation can reduce labor costs, remove or reduce safety risks, increase productivity, and establish better control over product/work quality. Labor requirements may be reduced in tasks where robotic machines are applied. This may especially be the case where manual labor is numerous and repetitive in nature. Work site safety is a primary concern and should be an objective when automated applications are considered. Arduous, laborous tasks can tire workers, especially during extremes in weather conditions. Automation that reduces worker exposure to harsh chemicals, traffic conditions or work processes should be encouraged. The quality in construction and maintenance work has the

potential to be greatly increased with automated applications. Achieving consistency in highway construction and maintenance quality would yield in a better overall product lasting longer and requiring less maintenance. Quality control is the checking of on-going procedures to a set of established standards. Automation would be ideal in this area since it can instantaneously measure the current field conditions, compare with a designated standard(s), and then execute any applicable changes in the work process to restore compliance. Productivity is another attribute where automation can have a positive impact in roadway construction and maintenance. By automating the repetitive, arduous tasks, productivity will increase since factors involving worker fatigue, weather extremes, and site-specific characteristics would be minimized.

The INDOT may decide to evaluate the applicability of some of the automated devices developed under the auspices of Strategic Highway Research Program (SHRP), particularly those related to construction and maintenance work zone safety. The INDOT may, at the same time, continue to monitor the progress of research and development work being performed by other state agencies for possible future implementation. The use of automated pavement and bridge condition inspection can, however, be pursued in the near term.

CHAPTER 10. INTELLIGENT VEHICLE/HIGHWAY SYSTEMS (IVHS)

Concerns about increasing traffic congestion in many areas of the country have fueled the application of advanced technologies for traffic operations. The feasibilities of many such technologies are being studied in the U.S. as well as in Europe and Japan. Many advanced technologies are currently being implemented and used successfully for improved roadway operation.

Advanced technologies in traffic operations are commonly categorized as Intelligent Vehicle/Highway Systems (IVHS). The proper implementation of IVHS technologies can result not only in increased capacity and efficiency of existing roadways, but also in substantial benefits in terms of user cost savings and air quality enhancement.

Concerns that the U.S. may be lagging behind Europe and Japan in the use of IVHS resulted in the U.S. Congress directing the U.S. DOT to prepare a state-of-the-art study on IVHS. This study (USDOT 1989) reviewed current developments and outlines a research and development program for the U.S. There are many projects underway throughout the country, involving the Federal Government, state and local governments, universities, and the private sector. French (1990) summarized IVHS projects underway in the U.S. and world wide. Transportation Research Board (TRB 1991) also recently

completed a state-of-the-art review of IVHS.

IVHS is a term that encompasses many advanced technologies. These are generally grouped into four areas: Advanced Traffic Management Systems (ATMS), Advanced Driver Information Systems (ADIS), Commercial Vehicle Operations (CVO), and Automated Vehicle Control Systems (AVCS) (Euler 1990). Following are discussions of each of these four components, the costs and benefits of IVHS, and the implications of IVHS in Indiana.

10.1 Advanced Traffic Management Systems (ATMS)

Advanced Traffic Management Systems (ATMS) involve the surveillance and control of arterials, freeways, and corridors. ATMS extract relevant traffic flow data from roadway detectors and use this information to automatically implement efficient traffic control strategies. Examples of such strategies are modified signal timing of an arterial network or real-time highway user information on a freeway corridor. Several states with large urban areas have successfully reduced congestion problems by implementing such traffic control strategies. In an interview with the study team, the personnel at the Michigan DOT involved in the Detroit surveillance and control system indicated that the system was estimated to be equivalent to an additional traffic lane in each direction.

Surveillance is an important component in ATMS. Most ATMS perform incident detection and traffic data collection using inductive loop detectors. This includes detection of

both recurring (normal traffic) and nonrecurring (incident induced) congestion. Once detected, incidents can be checked using closed circuit television. However, placing large numbers of loops in currently operating roadways can prove difficult and costly.

The Wide Area Detection System (WADS) is a surveillance tool which holds promise (Michalopoulos 1991) (Figure 10.1). Although the system has not been fully developed and tested, it is being used in Japan with fair success. Moreover, the feasibility of WADS is being investigated in several U.S. states. WADS uses automated video image processing to measure relevant traffic flow parameters. The cameras used in the system capture all lanes (in a single direction) of the roadway. Thus, numerous detection devices (located side by side) are not required. More importantly, the WADS cameras capture a large longitudinal segment of the roadway. Thus traffic flow parameters can be measured over a distance (as opposed to traditional detectors which collect "point" measures). It should be noted, however, that WADS is not yet commercially available in the U.S.

In addition, the real-time video image created by WADS can be used for visual inspection by personnel working in the operation center. Although WADS has a rather high capital cost, it is relatively inexpensive to maintain. On shortcoming, however, is that the reliability of WADS deteriorates because of occlusions as well as under inclement weather conditions and/or darkness. Moreover, any surveillance and control system should ideally be equipped

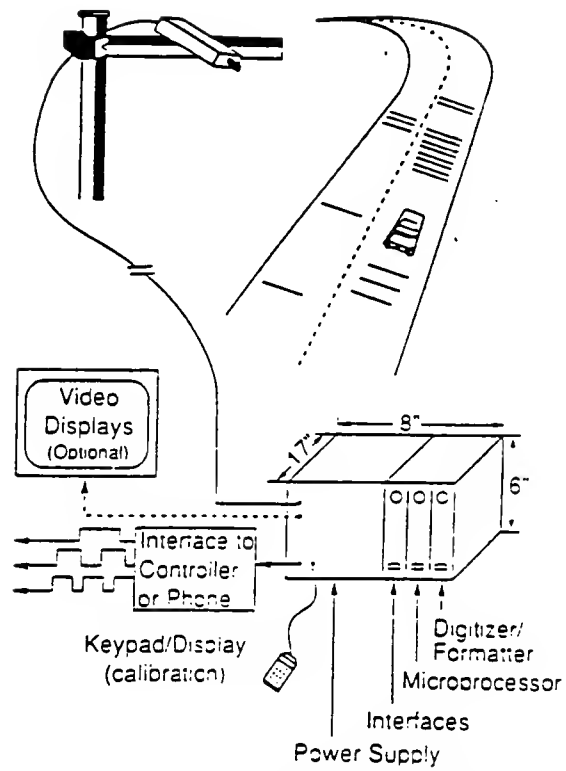


Figure 10.1: Wide Area Detection System
(Source: Michalopoulos 1991)

with back up surveillance systems to accommodate inevitable malfunctions. Therefore, "backup" surveillance equipment should be employed. Recent research at the University of California suggests that ultrasonic detectors are a reliable means of traffic surveillance. These devices should be located above the roadway to detect the presence of vehicles as they pass directly under. Detectors which horizontally detect vehicle presence do not work well on multilane facilities. A number of other types of optical or radar detectors could prove feasible as well.

Once an incident (or recurring congestion) is detected, a number of traffic management strategies can be employed. Strategies that other states have found to be successful include ramp metering, highway user information systems, real time signal control on adjacent arterials, and the use of roving emergency response and service patrols.

Ramp metering can be used to regulate freeway demand and thereby reduce freeway congestion problems. Ramp metering is now used in several states. For some applications, metering rates are determined off-line and used to minimize recurring congestion.

Real-time traffic information from detectors can be used for establishing variable metering rates. At the present simulation programs can also be used to develop a set of metering strategies based on categorized flow conditions. The FREQ simulation model, for example, can be used for establishing metering rates (Imada and May 1985). In coming years, expert systems can be employed to develop and use

self-adaptive ramp metering strategies.

Ramp metering and Highway User Information Systems can be used to divert traffic from the freeway to the surface streets. In this way, motorists avoid congestion by travelling around it. However, once traffic is detoured to surrounding surface streets, management strategies must be used to insure that acceptable operation occurs on arterials and highways.

The Automated Traffic Surveillance And Control (ATSAC) System in Los Angeles, California represents the first stages of an automated control system for surface streets (Rowe 1991). The ATSAC system currently controls 422 signalized intersections in several areas of the city. A total of about 4,000 intersections will be part of the system by 1998. The system uses loop detectors to obtain real-time traffic information. This information is displayed to centrally located monitoring personnel on color-graphics monitors. Figure 10.2 illustrates ATSAC system architecture.

A supervisory computer interfaces between system operators and all system equipment. (The core software used is the UTCS Enhanced package developed by the FHWA). The signal control strategies currently used in the ATSAC system are not particularly complicated. Most of the signals in the system generally operate under fixed time control (based on time of day). Timing was established off-line using the TRANSYT program (Robertson 1968).

About 25% of the signalized intersections in the ATSAC system operate under Critical Intersection Control. A real

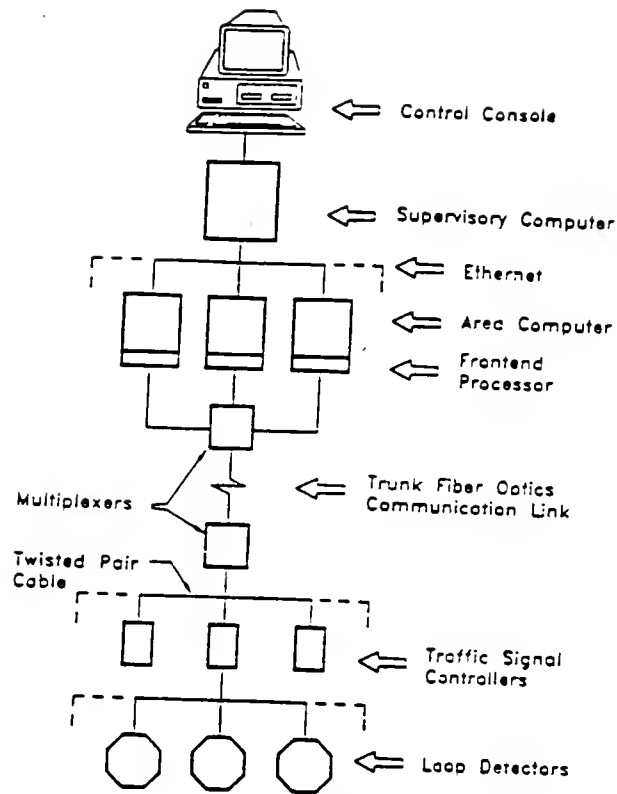


Figure 10.2: ATSAC System Architecture
(Source: Rowe 1991)

time algorithm automatically modifies green time splits based on traffic demands detected by the loops. This timing strategy is updated each cycle (Rowe 1991).

Under some traffic flow conditions, the signals operate under automatic traffic responsive control. Under this control, a signal timing plan is automatically selected by a computer algorithm which matches the real-time surveillance data with data used to create the timing plans (off-line) for fixed time control.

During severe incidents, manual override can be applied to a single traffic signal, or a group of signals. The manual override procedure requires that Operations Center personnel be sufficiently skilled to sort out (from large amounts of displayed information) those traffic situations that are beyond the bounds of the existing automated control techniques, and then to quickly make appropriate responses.

In the near future, expert system technology can be used to develop more efficient arterial management strategies. Using real-time traffic information collected by detectors, a central or area computer automatically determines a "best guess" signal timing strategy. The intersections are continually monitored and timing adjustments are made continuously, based on resulting impacts of each timing adjustment.

Expert systems can also be used to identify nonrecurring congestion conditions which can best be alleviated by manual override procedures. The expert system would provide the operator with decision support functions (based on previous

experience) of the most effective responses to different categories of nonrecurring events. Individual controllers at each signalized intersection would allow for isolated operation (i.e. graceful degradation) under system failure. Furthermore, the expert systems will function alone when the traffic operation center is not staffed (e.g. late nights, weekends, etc.).

Communications is another important aspect of ATMS. Data must be transmitted from the surveillance equipment to a central processing area, and communication must be maintained with signal controllers, changeable message signs (CMS), and other aspects of the system. This is usually done with buried communication lines. However, other promising technologies such as satellite communications, wide area radio networks, and compressed video are also being investigated.

Several options exist for communication lines. The capital cost is highest for fiber optic lines. However, fiber optic cables will function even when damaged. Fiber optic lines are laid in a closed loop and can transmit information in either direction, if one of the lines is damaged. However, they require some expertise to install.

Assessing a unit cost for these surveillance and control mechanisms is difficult. It can be noted, however, that the Los Angeles DOT estimates the benefit to cost ratio for the current ATSAC system to be almost 10 to 1, with implementation costs of approximately \$70,000 per intersection. Los Angeles DOT decided upon fiber optics due to large amount of data which had to be transmitted.

10.2 Advanced Driver Information Systems (ADIS)

Driver information technologies involve presenting up-to-date travel information to the traveler to aid in navigation. Such travel information could include traffic and congestion information, construction areas, detours, incident locations, alternate routes, weather information, and tourist information. When ADIS include tourist information such as hotel locations or parking, they are sometimes referred to as Advanced Traveler Information Systems or ATIS.

With the ability to collect real time traffic information via traffic detectors and freeway surveillance, the potential in this area is just beginning to be realized. Methods already being used to disseminate information to travelers include variable message signs, Highway Advisory Radio (HAR), commercial radio and television, and dial-up phone services. These methods are referred to as highway user information systems. The survey conducted in the study indicated that most of the states using these methods perceive high benefits from their use.

ADIS refers to other more advanced technologies such as electronic route planning, on-board routing advice systems, and on-board navigation systems. There are a few states with large urban areas that are just beginning to experiment with these technologies in cooperation with the automotive industry, and there are some products available commercially. Florida is one such state where an experimental program has just been initiated in the Orlando area. More extensive efforts are occurring in Europe (Rillings and Betsold 1991)

and Japan (Kamashima 1991).

Electronic route planning systems aid travelers in selecting routes, by allowing them access to electronic databases. They are based on videotext/teletext systems, in which subscribers access the electronic databases via telephone lines using a personal computer or a television screen with a keyboard. The databases can include any current travel information, and this information can be displayed on electronic maps. Several electronic route planning systems are already being used in Europe (Catling and McQueen 1991).

On-board routing advice systems use visual aids and/or audio instructions to aid drivers in route selection. A driver enters a destination via a keyboard and a shortest path algorithm is used to compute the best route. The more advanced systems take into account real-time traffic information. One system being developed in the U.S. can detect driver errors and automatically prepare revised directions.

These routing advice systems rely on Automatic Vehicle Location (AVL). AVL involves the use of on-board compasses and odometers (self-contained/dead-reckoning navigation systems) or radio waves from towers and/or satellites (eg. LORAN-C or GPS) to continuously or intermittently track the location of vehicles.

On-board navigation systems refers to electronic maps called up and used by the driver to aid in navigation. The use of on-board navigation technologies in combination with AVL technologies would allow the driver to track the vehicle's

course along a map. Enhancing on-board navigation systems with current traffic, weather, and parking information is being investigated as well.

The Michigan DOT plans to use a navigation system in which cars are sent information as they pass certain spots in the roadway. With such a system it would be possible to present information using text, speakers, or overlaying information on a map. Static information such as tourism information could also be stored in on-board computers. The Pathfinder project in California is demonstrating similar technologies. Figure 10.3 illustrates the pathfinder system.

Automatic Vehicle Identification (AVI) may also be included in ADIS. AVI involves the use of an interrogator/receiver built into the roadway and an electronic license plate or transponder tag attached to the vehicle that can be read via light, radio waves, or microwaves.

Currently, some states are testing the use of AVI to automatically assess tolls at toll plazas. Inexpensive microwave transponders have been read accurately at speeds of up to 35 mph through toll gates in California. Electronic toll collection would significantly reduce congestion at toll plazas.

AVI could also be used for assessing congestion tolls or parking fees automatically. Experiments in Hong Kong have shown that AVI could be used to implement road or congestion pricing.

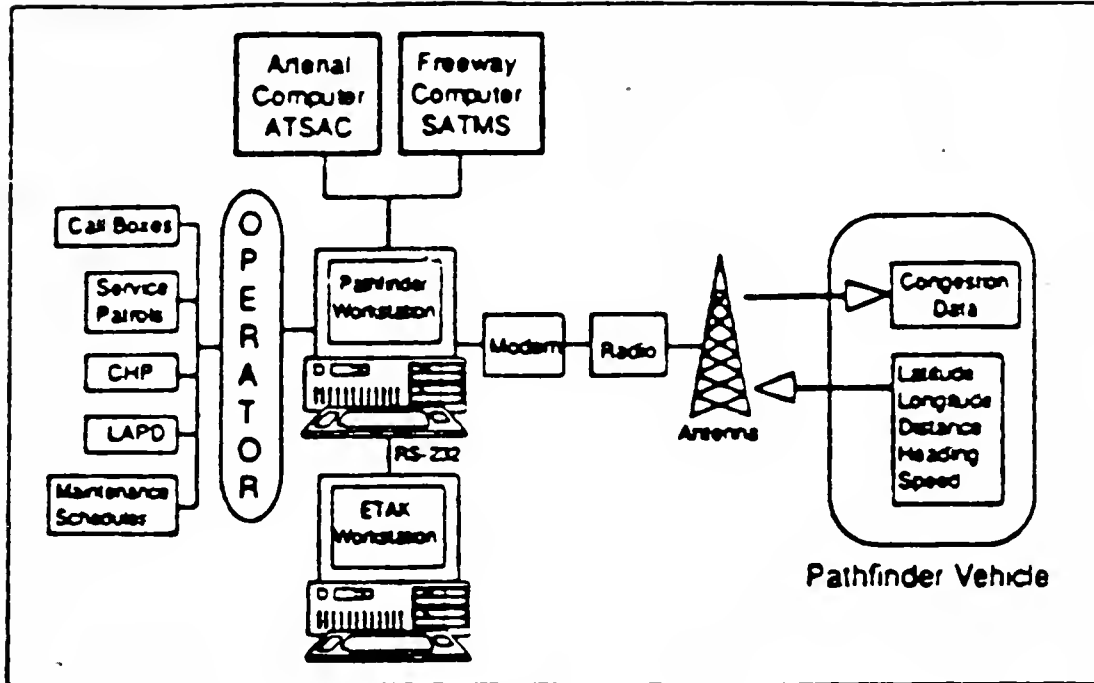


Figure 10.3: Layout of the Pathfinder System
(Source: Reoper and Endo 1991)

10.3 Commercial Vehicle Operations

In addition to ADIS, AVI and AVL can also be used to monitor heavy vehicles or emergency vehicles. Many government agencies and private firms are pursuing these technologies.

Several western states are involved in the Heavy Vehicle Electronic License Plate (HELP) program and the Crescent project (Walton 1991). These programs are testing the use of AVI, along with weigh-in-motion (WIM) technologies, satellite data links, and on-board computers for automatically identifying, weighing, and assessing fees to trucks. This would minimize the need for trucks to stop at weigh stations and ports of entry. Very detailed information could be collected, as transponders can include a variety of shipping data along with a unique identification number.

Kentucky is leading a group of several states and the province of Ontario that are evaluating the use of AVI for truck traffic monitoring on the I-75 corridor. Other possible applications of AVI include checking compliance with licensing and hours of driver service and truck safety regulations, as well as tracking the movement of hazardous materials.

AVL is of primary interest to freight fleet operators which would like to monitor freight movement to improve efficiency and select routes. It is being widely adopted by commercial and public service vehicle operators. It could be used in conjunction with on-board computers (vehicle management systems or VMS) that record information on mileage, speed or other items of interest. These computers would also allow drivers to input and retrieve information on fuel

purchases, delivery instructions, or even display maps.

Two companies in the United States, Motorola and II-Morrow, which is a subsidiary of the United Parcel Service, are currently marketing AVL systems based on LORAN-C and two-way radio for communication with the dispatcher. An electronic map is used in the dispatch office to track the movement and status of the vehicles, and the dispatcher can guide the vehicles out of congested conditions. Two other companies, Geostar and Qualcomm, are marketing similar systems which utilize satellites (Jacobs et al. 1991), and a system to supply real time traffic data to motor carriers is being tested in New York (Batz 1991).

Government agencies would be interested in AVL for determining trends in truck routing and calculating the number of trucks that bypass weigh stations. Thus this technology could also be a special purpose traffic data collection tool.

The Transportation Research Board recently investigated the costs and benefits associated with the implementation of AVI and AVL in a study on the feasibility of a nationwide heavy vehicle monitoring program (TRB 1986). It was found that many parties were interested in these technologies, and that they could provide very cost-effective methods of data collection. However, it was also pointed out that many legal problems might arise from mandatory implementation of AVI and AVL, and that there was a need for standardization and/or improvement of some of these technologies.

10.4 Advanced Vehicle Control Systems (AVCS)

Automatic Vehicle Control encompasses many technologies that can aid the driver in operation of the vehicle. These include radar braking, automatic headway control, automatic lane keeping, machine vision, and even replacing the driver completely.

Automatic headway control and lane keeping could allow vehicles to travel closer together and decrease the required lane width, which would increase capacity. Total trip automation could be achieved either by electrified highways or automating the vehicle independent of the highways. The California DOT is investigating the concept of electrified highways (Shladover et al. 1991). These technologies have the capability of improving safety as well as traffic flow.

10.5 Future Impacts of IVHS

The benefits of deployment of IVHS technologies are hard to quantify. However, in the 1990 Mobility 2000 meeting, benefits were identified and projected into the future and a framework of analyzing and categorizing IVHS benefits was developed (Mobility 2000 1990). Mobility 2000, an informal organization of government, industry, and university researchers, ushered the formation of IVHS America the purpose of which is to promote the use of IVHS. It is realized that estimation of benefits of IVHS is a process that must be updated over time and there is a committee within IVHS America that monitors and projects benefits.

The primary areas of benefit of IVHS are safety,

congestion, energy use, air quality, increased mobility, and infrastructure improvements. In addition, other non-operational benefits would be accrued, such as the market opportunity for the automobile and electronic industry, benefits to the research and educational community, and possible unplanned spin-off technologies. Benefits would be spread among numerous impacted groups, including user groups (urban, rural, elderly, suburban commuter), non-users, public sector, and private sector.

A four phase implementation schedule was foreseen by the Mobility 2000 group. During phase 1, IVHS will not likely be fully developed in any city in the U.S. ATMS will continue to be developed in various cities, and ADIS applications will continue to be demonstrated. However, full integration of ATMS and ADIS will not occur immediately.

Vehicle based (independent of the highway) AVCS, or AVCS-I, is projected to penetrate the market place to a 1% level during phase 1. Based on the successes of existing ATMS, a 15% reduction of congestion has been projected at an annual value of \$1.2 billion for applying simple traffic management systems alone. Projecting lifetime maintenance costs of ATMS and 15% congestion reduction for various cities resulted in benefit/cost ratios ranging from 1.3 to 3.2, depending on city size.

During phase 2, a few cities will have fully developed ATMS systems and the interrelationship between ATMS and ADIS will begin to be realized. Penetration of AVCS-I into the market place will increase to 5-10% and cooperative

driver-vehicle-highway AVCS (AVCS-II) technologies will just begin to penetrate the market place. Projected decreases in congestion range from 25-40%.

During phase 3, integrated ATMS and ADIS systems will be realized. Market penetration of AVCS-I is projected as high as 50%, as high as 25% for AVCS-II, and automated highway technologies (AVCS-III) will begin to penetrate the market place. Estimation of safety benefits in terms of lives and injuries saved by AVCS alone at this time ranges from \$4 to 22 billion annually. This does not include safety improvements resulting from overall improvements in traffic flow due to IVHS. After this point (phase 4) completely automated highways will begin to emerge, and congestion reductions are projected to range from 30 to 50%, taking into account increased demand likely to be sparked by decreasing congestion.

Commercial vehicle applications of IVHS are expected to take place at a more rapid rate. In fact, many private firms are already pursuing IVHS for fleet monitoring and control, indicating that they are already finding the implementation of IVHS to be beneficial.

10.6 An IVHS Program

Many interrelated issues arise when implementing IVHS technologies. Capital costs are high and benefits are hard to quantify. IVHS implementation involves many complex technologies, and new developments occur constantly. In addition, agency personnel will initially have little

experience with IVHS. To overcome the complex issues and develop a successful program, a structured IVHS program to systematically evaluate and implement IVHS technologies is needed.

States that are at the forefront in the implementation of IVHS have developed such programs. Examples of states with comprehensive programs are Texas (Bridges 1989), Michigan (Chen and Ervin 1989), California (Vostrez 1989) and Virginia (Virginia Conference 1990). Ingredients common to the IVHS programs in these states include:

- 1) Keeping informed of new developments,
- 2) Coordination and cooperation with other interested parties,
- 3) Applying an incremental approach,
- 4) Allowing flexibility for future developments, and
- 5) Organizational restructuring, and training and reorienting existing staff.

With the large increase in IVHS activity, it is important to keep informed of recent developments. After an initial literature review, agencies need to keep abreast of new developments by joining organizations, such as IVHS America, attending conferences, receiving IVHS publications, and seeking out and communicating with private sector representatives. This will also serve to foster cooperation with other involved parties.

Coordination with the universities, the private sector, and state, federal and local agencies is key to the success of IVHS. This allows for multiple funding, pools resources, speeds up implementation time frames, and helps insure

compatibility with other available technologies. Most large scale IVHS efforts rely on private funding and technical assistance to some degree, from the automotive, electronics, computer software, or defense industries. For example, General Motors (GM) supplied vehicles equipped with on-board navigators for the Caltrans Pathfinder project (GM 1990), and Michigan is relying on support from Siemens to support its test of ADIS technology (Inside IVHS 1991). Universities should be called upon to help facilitate private-public cooperation and research. The ISTEA of 1991 also provided a significant opportunity for research and demonstration of IVHS in the next few years, which should provide a great incentive for states to get involved.

Coordination with other states is also necessary. This eliminates redundant efforts, allows agencies to build on what others have done, and helps to coordinate activities with adjacent states. It is important to collaborate across jurisdictional boundaries, both within the state and across state lines. There should be early involvement with all involved jurisdictions. Involvement of user groups should be sought as well.

After becoming informed of IVHS technologies, and initiating communication with other parties, technologies with the greatest potential can be identified. These should be applied in an incremental approach, investing in short term projects that have benefits now, but are also building blocks in future longer term demonstrations. Each state should add something new to IVHS research, expanding on what has been

done previously. When designing the system, flexibility needs to be included to allow for future developments. No standards have been established for sharing data within various systems. This may create some problems, especially in coordinating efforts between adjacent states. Standardization will need to be addressed before efforts can be coordinated nation wide. A plan should not be too rigid, because objectives and needs will change.

Finally, it is necessary to create an organizational structure within the agency to manage the technology. The management group will need to monitor IVHS developments elsewhere, actively seek cooperation with other parties, develop and maintain a long range plan, and identify, design and implements technologies. Existing staff will need to be reorientated and trained. Initially, assistance and consulting with experts outside the agency will be required. However, as agency personnel become experienced with the technology, and the emphasis of the agency's efforts begin to switch from analysis and design to implementation and demonstration, the agency will need to take a larger role in the administration of the technology.

10.7 IVHS in Indiana

INDOT is making considerable progress in the implementation of IVHS in relation to an FTMS on the Borman Expressway. The Borman Expressway, I-80/94 in northeast Indiana, links Gary, Indiana to Chicago, Illinois (Figure 10.4). It has the highest ADT of any road in the state,

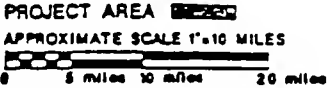


Figure 10.4: Overview of the Borman Expressway
(Source: HNTB 1990)

approximately 140,000 vehicles per day, with 25 to 70% trucks (Figure 10.5). Volumes remain fairly constant throughout the day, and operational problems are primarily incident induced. INDOT is developing an electronic surveillance and control system for a 16 mile section of the expressway adjacent to the Indiana/Illinois border.

As discussed previously, the principal components of a FTMS are surveillance, communications, service patrols, driver information, and traffic control. INDOT is in the process of designing and implementing a comprehensive FTMS addressing these issues. There is limited cost/benefit information available because the project is in the early stages of design.

Initial data collection activities have begun. Also, some preliminary data are available from previous studies. High speed portable WIM stations are now in place for both the east and westbound directions to classify, count, and weigh trucks.

Inductive loop detectors might be used in conjunction with video image processing for surveillance. These detectors will be linked to roadside controllers that will process the data before transmission. The consultant selected to design the system will include the purchase of video image processor (VIP) detectors. There are alternative devices available for VIP detectors. These will primarily be used to calibrate the loop detectors. The Autoscope, a type of VIP detector developed, at the University of Minnesota, is currently available for \$30,000 per unit (refer to Figure 10.2), but

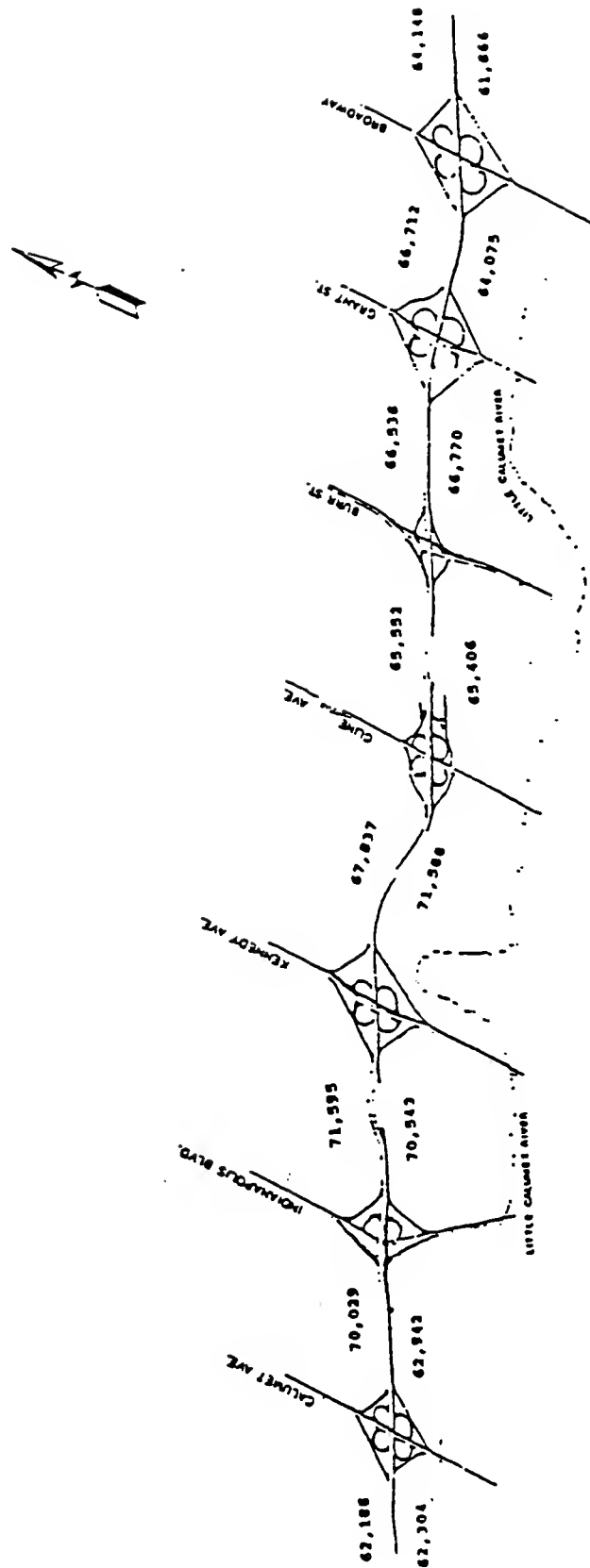


Figure 10.5: Borman Expressway Traffic Volumes
(Source: HNTB 1990)

prices are expected to fall in the future. The VIP detector being developed by Hughes Electronics is another alternative. The price per unit for such a device is expected to be in the range of \$25-30,000.

The most common method of accessing these detectors in FTMS is to build a conduit holding telephone lines or fiber optic cables adjacent the roadway. A surveillance system based on this type of communications system generally costs around \$1 million per mile in urban areas (Mobility 2000 1990). However, due to the rural nature of the Borman Expressway, it is expected that there will be fewer detectors needed than in other FTMS. Also, because of the expected use of pattern recognition algorithms, the need for frequent detectors will be eliminated. Thus placing communication lines in a conduit can be too expensive, and other methods of communication are being investigated.

A satellite communications system is one option being considered. This involves placing uplink units that communicate with the controllers and leasing satellite time to transmit data to a central traffic operations center (TOC). The cost of such a system is high at this point. However, this type of system has advantages, most notably the ability to communicate over long distances with no increase in costs. Thus it may be a useful tool if IVHS efforts spread state wide and prices fall, as it would allow traffic information from various parts of the state to be tied into a single operations center. For these reasons, a small scale test of the technology should not be ruled out. In addition, FHWA could

possibly sponsor a satellite to reduce individual state costs. Implementation of such a system would be through Department of Defense.

The most promising communications technology at present was found to be a wide area radio communications network. Transmitters hooked up to controllers will send data via radio waves. Video images from WADS detectors can also be sent via radio waves using a process referred to as "compressed video" marketed by Hughes Electronics and others. INDOT speculates that the reduced number of detectors needed and the use of a wide area radio communications network instead of buried communications lines will reduce the cost of the surveillance system significantly.

An advantage of radio communications is that data can be sent in more than one direction to more than one location. Detector data will be sent not only to the TOC but to service patrol vehicles equipped with on-board computers as well.

Service patrols composed of four-wheel drive king-cab one ton trucks are being implemented. Alarms and decision support will be sent from TOC to service patrols. Each vehicle can be equipped with a changeable message sign (CMS), extra fuel, other equipment to aid stalled vehicles, and a push bumper to move disabled vehicles off the expressway by the nearest shoulder or off-ramp. The overwhelming majority of incidents involve small passenger vehicles.

In addition, service vehicles will contain a revolving list of local wrecker services and a cellular phone for contacting these services. Mileposts have already been

installed at 1/10 mile intervals to aid in communicating the exact location of incidents.

The service patrol program will benefit wrecker services and emergency response agencies as well as the traveling public. Thus the program will be a cooperative effort between other state agencies, wrecking services, and INDOT. Travelers will be given an evaluation card in order to monitor the performance of the wrecking services and the service patrols. It should be noted that this patrol program has been implemented as of September, 1991.

The program will also catalogue accidents for later analysis. This will help to identify the benefits of the system. The data can be used to correlate accidents with detector data to determine the relationship between accidents, incidents, and changes in various traffic parameters. A detailed record of incidents is now available and the record will be expanded in time.

Detector data will be sent to the TOC. Initially, the TOC will be housed in a temporary facility, and used by INDOT and consultants for data collection. Video images from the VIP detectors will be sent to the TOC along with vehicle data. Eventually it will be used to manage advanced traffic control strategies as well.

After an incident has been detected, changeable message signs (CMS) can be accessed by the TOC using radio waves and cellular phones to communicate information on delays and possible detours to drivers. Other driver information technologies will also be investigated in the future. Detour

contingency plans are currently being developed to aid in selecting rerouting options.

Several closed-loop signalized intersections exist on adjacent roadways (Figure 10.6). The TOC will also call up the controllers at these intersections and alter signal timings to facilitate the rerouted traffic.

An accurate simulation model is required to optimally select operational strategies including detour options. Purdue University is developing a simulation model for the Borman mainline, and it will be calibrated using data being collected at present. In the future the simulation model can be expanded for the Borman corridor.

The TOC will also aid in incident detection by including information from travelers. Incidents are primarily identified using detector data. This is most frequently done using the "California Algorithm", a mathematical procedure that uses data from detectors to identify possible incidents, but there are some problems with the procedure. Therefore, INDOT needs to develop a new algorithm. However, these procedures will probably still give occasional false alarms and miss some incidents. Thus it is beneficial to augment incident detection methods with cellular phone calls and CB radio messages from travelers.

The TOC will add these capabilities by allowing CB radio to be monitored and calls from motorists to be received. Lake County in Indiana has a successful program in which 911 calls from cellular phones are transferred directly through the police. INDOT is working closely with the Chicago Area FTMS

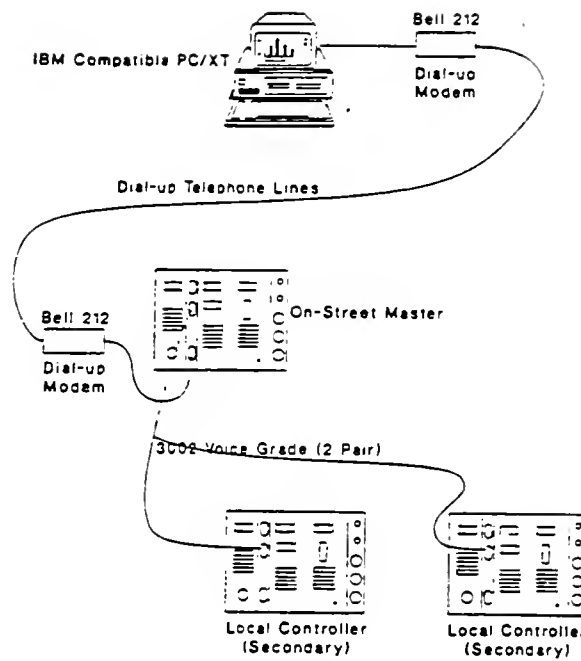


Figure 10.6: A Schematic of Closed Loop Signal Systems
(Source: Haver and Tarnoff 1991)

personnel sharing information with Chicago. Coordination of the two systems will benefit both parties and the users.

A two phase design and implementation plan has been developed by INDOT for the Borman Expressway FTMS. Phase I will last 12 to 18 months, and will include data collection activities, development of a simulation model by Purdue University, detour contingency planning, development of an incident detection algorithm, implementation of service patrols/incident response crews, implementation and testing of CMS, a temporary TOC, and overall system architecture. During this phase CMS will be moved from place to place to determine optimal placement of signs. This will also allow testing and refining of detour options. INDOT will work closely with the Chicago Area system during phase I and develop a method of coordinating activities with this system. Phase I will cost \$1.7 million including manpower, consultants, salaries, and equipment.

Phase II will involve complete implementation of the system. INDOT estimates the entire project will cost between \$6 to 15 million. Reconstruction is scheduled for five of the interchanges on the Borman during the duration of the project and noise barriers will also be added. Construction on three of the interchanges has already begun. This scheduled construction makes the detour contingency planning and refinement of CMS placement of the utmost importance.

The Borman FTMS project will serve a secondary purpose apart from relieving congestion on the freeway. It will also

provide a test of these technologies so that what is learned can be applied elsewhere in the state. Two areas that may also benefit from IVHS are the I-65 regions near Louisville, Kentucky and in Indianapolis. A possible phase III expansion of the Borman FTMS is also foreseen, where it will be expanded south on I-65 to US 30, and east on I-94 to the Michigan state line (Figure 10.7). Real time traffic adaptive signal control on nearby roadways will also lay groundwork for implementing IVHS for urban arterial network management in selected cities. In addition, the basic FTMS will lay a foundation for other more advanced technologies such as ADIS, AVI, and AVL to be tested or added in the future. No plan exists now to implement these technologies in Indiana.

INDOT does, however, have an extensive WIM project currently under development. As mentioned previously, several states are demonstrating WIM and AVI as part of a potential nationwide heavy vehicle monitoring program. INDOT's new WIM project may be the first step in an eventual AVI program in Indiana.

The project involves the installation of 30 permanent high speed WIM stations. Half the stations will be placed at various locations where SHRP data are to be collected, while the remaining stations will be placed on interstate entrances to the state.

It is expected that these stations will yield weight data within an accuracy of 10%. They will also classify vehicles and send data by telemetry. Data will automatically be in FHWA HPMS (highway performance monitoring system) format as

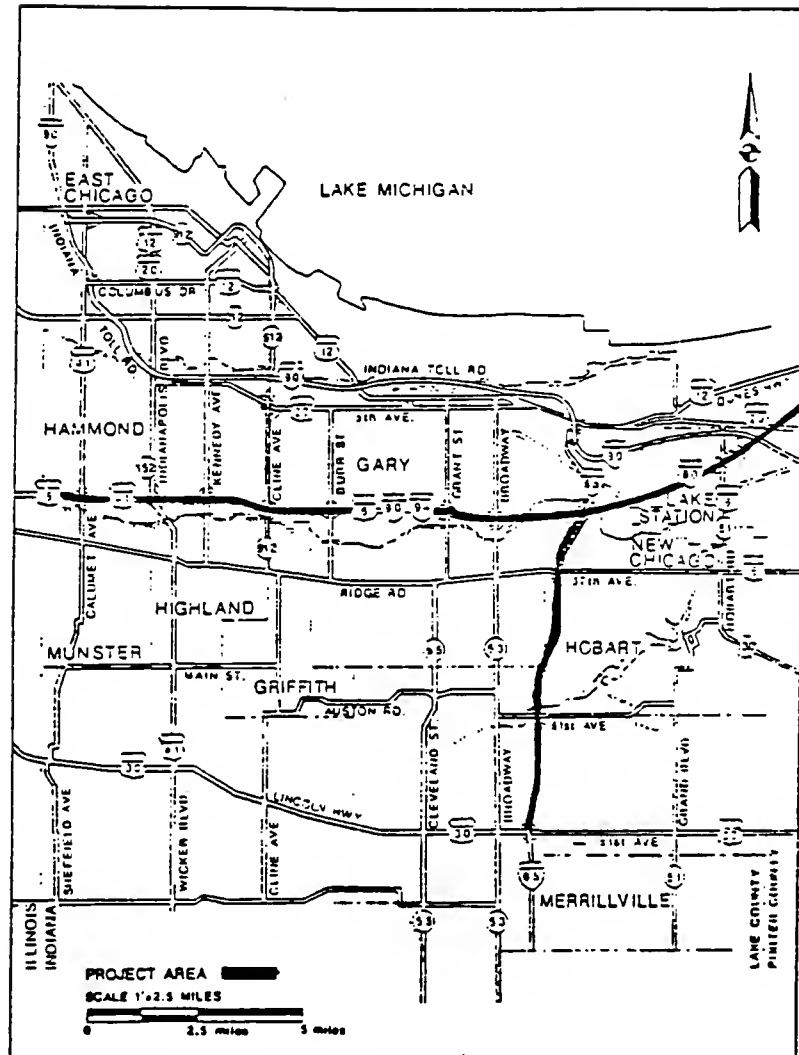


Figure 10.7: Possible Phase III Borman FTMS Expansion

outlined in the Traffic Monitoring Guide and required by the FHWA. Some of the sites may be useful as HPMS sites, but some may not, as they are not being placed according to FHWA guidelines.

In addition, low speed WIM and portable high speed WIM/AVC equipment is currently used in Indiana. The state police use low speed WIM as screening devices at two weight enforcement stations on I-94. After trucks leave the freeway via the weigh station ramp, they drive over low speed WIM equipment. The equipment signals the drivers to either stop for more accurate static weighing, or bypass the weigh station. These stations decrease delay to legal trucks that pass through the station, but are not relevant to data collection.

The portable high speed WIM program is used to collect truck weight and classification data, and is tied into the HPMS program. A portable capacitance plate is placed to collect weight data in one lane of the roadway, while classification is generally done for the whole side of the roadway. Data are sent to a roadside data collector, and later uploaded into a laptop computer.

The portable WIM program allows considerable amounts of truck data to be collected. Prior to the use of WIM, data were collected at road side static weigh stations. Truck drivers pulled into the station and went through a lengthy interview, static weighing, and classification procedure. The large amounts of data required by the FHWA meant that a weigh station crew might only be able to collect data for 3,000

vehicles in an entire summer. Furthermore, data collected in this manner are highly biased, as overweight carriers avoid the station. This is grossly inadequate in attempting to accurately characterize statewide truck traffic.

With the emergence of WIM, the FHWA waived the driver interview portion of data collection requirements for data collected using WIM. The extent of the data to be collected is still quite high, but portable high speed WIM/AVC equipment can weigh and classify 3,000 trucks in one day. These data will not be as biased either.

INDOT's high speed WIM equipment provides summary information on the data collected. These data are integral input to planning, pavement design, and pavement management. However, the data are not collected in FHWA format, and there is no translation software to allow the data to be translated into FHWA format. Thus the extensive amount of data collected are not useful in fulfilling FHWA guidelines. Furthermore, once the data are collected, they are difficult to access. Often the various divisions can not reach the data in the database, so it is not very useful in INDOT. A project to develop translation software has been proposed within INDOT. Data summaries will be sent to FHWA in their present format in the near future to see if they will be accepted, but this is not likely.

10.8 Costs and Benefits of IVHS

The costs of advanced traffic management systems are quite extensive. They include system development,

communications, construction, instrumentation, maintenance, and management costs. Costs can be reliably estimated, but detailed costs can not be assembled until the final designs for each element of a traffic management system are completed.

The Mobility 2000 group provided general estimates of costs for state-of-the-art FTMS and advanced signal control systems (1990). Costs for a typical urban FTMS including detectors, CMS, ramp metering, and communications were estimated as \$500,000 for an areawide planning study, \$7.5 million for areawide system design, \$1 million per mile for construction, and 10 to 15% of total construction costs for annual operation and maintenance. Additional costs for signal systems with extensive state-of-the-art monitoring capabilities, comprehensive state-of-the-art communications, modern controllers, and a modern TOC were also estimated. Costs of this type of system would add an additional \$2,000 per intersection for design, and \$40,000 to 20,000 per intersection for construction, depending on area size. Annual operations and maintenance could also be estimated at 10 to 15% of construction costs for advanced signal control systems.

Cassidy and Sinha (1990) outlined costs for various elements of a proposed FTMS on the Borman Expressway. They suggest total costs of a comprehensive FTMS can be estimated as \$1 million per mile for design and implementation, or \$12 million for the Borman, with annual operating costs 10% of the total system costs, excluding costs of service patrols. INDOT estimates costs will range from \$6 to 15 million for the entire system, depending on the technologies used.

Reliable estimates of the benefits of FTMS are harder to quantify. These benefits include reduced travel time, reduced fuel consumption, reduced emissions, increased travel speeds, and increased safety. Reliable estimates of the benefits for various strategies are essential, given the extensive costs of these systems, for system optimization. Simulation modeling of traffic operations under various strategies is the best method for evaluating system benefits.

A variety of traffic simulation models for freeways and corridors are available (Van Arde et al. 1987, May 1987). Accurate simulation requires reliable estimates of operating conditions and a reliable model. Operating conditions include all relevant traffic, geometric, and control data. These data can be collected. Insuring that a model is reliable requires calibration.

Most simulation models have sensitivity parameters that can be used to calibrate the model. These parameters reflect site specific behavior such as free flow speeds, gap acceptance criteria, and vehicle performance characteristics. Calibration involves adjusting these parameters so that observed operating characteristics match simulation predictions derived using the same input.

As mentioned previously, INDOT has just began data collection on the Borman, and a simulation model is under development but not yet available. In lieu of accurate traffic data and a simulation program, queuing theory can be used to provide a rough estimate of the benefits of reducing incident induced delay using ATMS.

Delays from incidents are significant. A vehicle stalled on the shoulder of a 3-lane freeway has been shown to decrease traffic flow by 28%, and an incident blocking one lane by 50% (TRB Circular 326 1987). Vehicle delay resulting from three types of "typical" incidents on the Borman Expressway was estimated, using queuing theory, based on the limited existing traffic data (Cassidy and Sinha 1990). These included: scenario 1 - a vehicle stalled in the westbound shoulder lane at 8:00 am for 1/2 hour; scenario 2 - a vehicle stalled in the eastbound shoulder lane at 4:00 pm for 1/2 hour; and scenario 3 - a major eastbound incident blocking 2 of 3 lanes at 4:00 pm for 1 hour. The delays resulting from these incidents are listed in Table 10.1, and the traffic data and assumptions used in the calculations are listed in Appendix B.

Assuming that electronic surveillance and service patrols reduce incident detection and response times by 15 minutes, would result in total vehicle delays as listed in Table 10.2 for the same three incidents (calculations in Appendix B). The resulting differences in delay and congestion between the two sets of incidents are listed in Table 10.3.

The data in Table 10.3 indicate that a slight reduction in incident duration will produce a significantly larger reduction in total delay. These calculations were performed under the assumption that no vehicles detour around the incident. Thus benefits would be even greater if driver information technologies and subsequent rerouting of traffic were taken into consideration.

The benefits of these reductions in delay, as mentioned

Table 10.1: Delay Resulting from 3 Typical Incidents on the Borman Expressway (Source: Cassidy and Sinha 1990)

| Scenario | Incident Duration (hours) | Congestion Duration (hours) | Maximum Queue Length (vehicles) | Total Delay (veh.-hrs) |
|----------|---------------------------------|-----------------------------------|--|------------------------------|
| 1 | 0.5 | 0.92 | 568 | 261 |
| 2 | 0.5 | 2.10 | 1,128 | 1,349 |
| 3 | 1.0 | 3.90 | 3,205 | 6,694 |

Table 10.2: Delay Resulting If Incident Response Time Reduced by
15 Minutes

| Scenario | Incident Duration (hours) | Congestion Duration (hours) | Maximum Queue Length (vehicles) | Total Delay (veh.-hrs) |
|----------|---------------------------------|-----------------------------------|--|------------------------------|
| 1 | 0.25 | 0.46 | 284 | 65 |
| 2 | 0.25 | 1.37 | 564 | 452 |
| 3 | 0.75 | 3.13 | 2,404 | 4,262 |

Table 10.3: Reduction in Delays From Reducing Incident Response by 15 Minutes

| Scenario | Reduction in Incident Length (hours,%) | Reduction in Congestion Duration (hours,%) | Reduction in Total Delay (veh-hrs,%) | Benefits of Saved Travel Time (\$) |
|----------|---|---|---|--|
| 1 | .25 (50%) | 0.46 (50%) | 196 (75%) | 980 |
| 2 | .25 (50%) | 0.76 (36%) | 897 (66%) | 4,485 |
| 3 | .25 (25%) | 0.77 (20%) | 2,382 (36%) | 11,910 |

previously, include fuel costs, reduced emissions, and travel time savings. Estimating fuel costs and emissions requires a calibrated model, but it is possible to make a rough estimate of the value of the reduction in travel time by placing a cost on travelers' time. This is rather difficult, as the value of time depends on various factors (e.g. trip characteristics, trip maker's characteristics, length of delay, and so on).

Many methods exist for calculating the value of travelers' time. One of the more conservative and simpler methods of estimating travel time costs for passenger cars is to multiply the minimum wage by an unemployment factor and vehicle occupancy rate, as used in the Chicago Area Transportation Study of 1961. Using factors of \$3.85/hour, 0.8 employed people, and 1.3 persons/vehicle results in a value of \$4 per vehicle-hour. Travel time costs are much higher for trucks because they represent actual market costs, and can be conservatively estimated at \$8.00 per hour. Using these figures and assuming 20% trucks in the traffic stream results in estimates of travel time savings as listed in Table 10.3.

These are highly conservative estimates. Other methods yield much higher costs for vehicle delay. Arizona has estimated costs of vehicle delay at \$10/hour, but it is not clear whether they are referring to trucks or passenger cars or both (Kurfees and Cline 1990).

These figures indicate that a user benefit of \$5,000 per incident in travel time savings alone due to reducing incident detection and response time by 15 minutes is a conservative

estimate. At this rate, 200 incidents per year would result in a net benefit of \$1 million per year in travel time savings. Including other benefits such as fuel savings and operation costs would result in much higher benefits. Mobility 2000 calculates that truck operating costs alone are \$23 per hour, regardless of the travel time costs of delaying goods delivery.

In fact, other states have received much higher benefits from implementing FTMS and incident response patrols. For example, the Chicago Area Minutemen program is one of the largest incident response patrol programs in the country. At a cost of \$5.5 million per year, an incident response fleet containing wreckers patrols freeways during peak hours. Chicago found that a one minute reduction in incident duration results in a three to five minute reduction in recovery time, and that reducing a 30 minute incident by 15 minutes reduces congestion duration from 90 to 45 minutes. These reductions are much higher than as calculated using queuing theory on the Borman. The Minutemen program saves travelers \$95 million per year, at a payoff of 17:1.

The Mobility 2000 group (1990) summarized benefits resulting from ATMS strategies that have been employed in several areas around the U.S. Travel time reductions of 27 to 39%, fuel savings of 2 to 7%, and hydrocarbon emission reductions of 8 to 13% have been recorded at various FTMS sites, even with simultaneous increases in traffic volumes. These benefits, however, are situation dependent, and vary with location.

The cost of WIM is primarily related to equipment purchase and construction. Manpower costs, once WIM is implemented, are lower than for static weigh stations. The costs for INDOT's permanent high speed WIM program are not available. However, the costs of implementing portable high speed WIM capable of monitoring 30 sites per year were \$180,000 in 1988.

Benefits of WIM accrue to the travelling public, the state agency, and legal carriers. Legal carriers no longer need to stop as often and experience lengthy delay at weigh stations. The state agency receives greater amounts of truck data for pavement design, pavement management, cost allocation, and other purposes to improve the various functions. In Indiana, the availability of truck related data increased phenomenally after the implementation of portable WIM, while in the past such data were difficult to obtain.

Improved truck data for cost allocation means that highway taxes can be levied more equitably, thereby benefiting the general traveling public. In addition, the public may receive safety and delay benefits in situations where trucks previously queued at weigh stations and overflowed onto the roadway. Labor costs for collecting truck data are also decreased.

The FHWA's Traffic Monitoring Guide recommends sufficient data collection to estimate the mean truck weights for each truck classification with 95% confidence and 10% precision for the entire truck population. NCHRP Report 303 found that temporary WIM/AVC sites could accomplish this for 5-axle

tractor semi-trailer trucks, and that it could be accomplished for all vehicle classes with the same number of permanent WIM/AVC sites. Thus WIM adds the capability for complete truck data collection, which Indiana did not presently have.

WIM was also found to be cost-effective for enforcement screening at weigh stations, if used to complement a comprehensive statewide enforcement program where enforcement is allocated to roads on the basis of VMT and augmented with random enforcement efforts. Benefits were measured in terms of reduced pavement damage. However, most states allocate too little effort to enforcement for these benefits to be substantial. It was also found that doubling overweight fines could be as effective as doubling enforcement effort.

Perhaps the greatest potential for WIM in the future is the use of high speed WIM in conjunction with AVI and AVC. This would allow very comprehensive truck data to be taken with minimal labor. AVI equipped trucks could bypass static weigh stations completely and be weighed using WIM, with data such as registration and goods carried read from an AVI transponder. Alternatively, trucks could be weighed once at the beginning of their trip and passed through subsequent weigh stations and points of entry that are equipped with AVI query capabilities and tied into a regionwide database. This can allow automatic assessment of possible weight-distance taxes.

AVI would also be useful for ATMS. AVI equipped vehicles could be tracked through the system and used to measure travel speeds and delays. It would also allow automatic toll

collection or congestion pricing. AVI continues to be tested at toll plazas for automatic toll collection at various locations.

NCHRP Report 303 found that AVI for preclearing and bypassing weigh stations would allow the average state to break even on its investment if 15% of the vehicles in the state used the system. This method would have little impact on illegal carriers, however.

10.9 Summary and Future Directions

Currently, in the U.S., traffic demand is steadily growing resulting in increasing congestion in many areas of the country. The FHWA has predicted that this trend will continue into the future. Consequently, it can be expected that the problems associated with congestion, such as increased air pollution, energy consumption, accidents and user costs, will also proportionally increase, unless some actions are taken now.

The state of Indiana is experiencing these congestion problems, particularly in the Northeast sections of the state. Being a cross-road state, Indiana also serves heavy volumes of truck traffic. IVHS technologies have been proven to decrease congestion and will provide improved methods for monitoring heavy vehicles in future years.

Even though some of the IVHS technologies are still in the testing stage, there are steps that can be taken now. State-of-the-art traffic management technologies such as incident detection and response, ramp metering, and driver

information have already been proven. Many of the IVHS technologies are based on FTMS systems. Therefore actively pursuing such systems is also a logical first step in preparation for future more advanced technologies.

INDOT is already making considerable progress in relation to a FTMS on the Borman Expressway. In addition, an extensive WIM program is in development involving 30 permanent high speed WIM stations, half of which will be placed at interstate entrances to the state. Portable high speed WIM is also used. These programs will be beneficial in the near term. They will significantly decrease congestion related costs on the Borman, and increase the quantity and quality of truck traffic data. Furthermore, they will provide a base for the testing and implementation of other IVHS technologies in the future, and should be viewed as part of a long term phased IVHS plan, involving possible future Federal programs and support from the private sector.

However, before INDOT can receive benefits from and build on AVI, a detailed study on the management of WIM and other traffic data is needed. Currently, many possible users can not access these data in a usable format. The proposed study should be undertaken immediately, and would identify all the data users and the formats they require, and develop methods of transferring the data in usable form to the specific users. These data are too valuable and costly to not use.

The Borman FTMS, in addition to alleviating near-term congestion problems, will expand the body of knowledge on IVHS technologies, through investigation of widearea radio

communications, video image processing, compressed video, and a new incident detection algorithm. As the system progresses, what is learned can be applied elsewhere in the state, and promising new technologies can be tested. Possible middle term projects include FTMS expansion projects, use of ATMS for arterial networks in selected urban areas, demonstration of ADIS, demonstration of AVI, testing of satellite communications, and development of expert systems for real time signal control.

As experience is gained and the technologies are proved, FTMS can be expanded elsewhere in the state. This can involve corridorwide expansion of the Borman system eastward on I-94, including parts of I-65 and US 30, as well as introduction of the technologies into other areas such as the I-65 regions near Indianapolis and Louisville, Kentucky. These areas also experience heavy traffic volumes, although congestion is more recurrent in nature.

If FTMS were expanded statewide, satellite communications may become more economical, as it would allow communication over large distances. Thus a test of this technology may be productive, especially if private sector support could be obtained from vendors, although prices may be prohibitive at present.

ATMS could also be applied to urban arterial networks in some areas. Remotely altering signal timings to accommodate rerouted traffic will be tested on the Borman. Experience gained here can be applied to selected locations. The Greenfield and LaPorte districts already have computerized

monitoring of signal systems to provide automated signal maintenance, and Evansville and Fort Wayne have had centralized signal control based on mainframes. These areas should be given priority in implementation of ATMS for arterial network control.

Developing expert systems that automatically change signal timings based on input from detectors is currently being investigated in some states. If INDOT develops an expert system program, then a demonstration of this technology on the Borman corridor or in another urban area would also be a viable mid-term project.

FTMS could also serve as a testing ground for ADIS technologies. These technologies involve the automobile manufacturing industry, the computer industry, and others which are experimenting with sophisticated in-vehicle guidance, location, and navigation aids. The location of Indiana, near the base of the automotive industry in Michigan, might allow INDOT to receive private sector support for the testing of these technologies, after FTMS become well established. However, a demonstration project involving these technologies would require coordination with the Chicago area FTMS.

Another feasible mid-term project may be the demonstration of AVI technologies, either in connection with toll collection, heavy vehicle monitoring, or congestion pricing. The FHWA is involved in demonstrating these technologies, and will likely be willing to fund more projects in the future. The Indiana Toll Road, the new WIM program,

and the city of Indianapolis are all potential testing grounds.

However, before AVI and WIM are implemented nationwide, AVI equipment standardization guidelines and a computer database that allows efficient sharing of data with other states would need to be addressed. Thus implementation of a comprehensive WIM/AVI program would be a long term project. ADIS technologies also need to be further tested, and integration of ADIS and ATMS into a comprehensive corridorwide system is a long term project as well.

As new technologies evolve, the long term goals of an IVHS program need to change. Personnel responsible for IVHS in Michigan DOT, in an interview with the study team, warned against development of a rigid and static IVHS implementation plan. It is more important to select technologies in an incremental approach, and leave future options open.

CHAPTER 11: A NEW TECHNOLOGY PROGRAM IN INDOT

As revealed by the state agency survey conducted by the study team, most state transportation agencies are pursuing advanced technologies to different degrees. Several states are leaders. These states have benefited from the development of comprehensive programs that systematically evaluate new technologies.

California is among the states that are pioneers in the use of advanced technologies. Caltrans has developed a comprehensive plan which includes general goals, an approach methodology, and a long range implementation plan (Caltrans 1990).

The general goals of a new technology program, as outlined by Caltrans, are to:

- 1) Provide technological alternatives to standard roadway improvements that will increase capacity and mobility while improving safety and quality of life,
- 2) Incorporate new technologies into day-to-day work that will increase productivity and efficiency and improve employee safety,
- 3) Manage new technology efforts efficiently, coordinating efforts among all participants to eliminate duplication, maximize the use of resources, and speed technology advancement.

A new technology program should be evolutionary in nature, with new products added incrementally. This means

placing emphasis on technologies which are not only useful by themselves, but are essential "building blocks" in the achievement of long range goals. For example, a freeway traffic management system is beneficial in the near term, but also serves as the base for future IVHS developments. Thus technologies must be applied strategically, allowing the flexibility to adapt to future needs as they are identified.

Initial investments should be allocated to technologies which offer the greatest gains in efficiency at the lowest capital costs, and are already available or closest to being available. Smaller scale demonstration projects are useful tools, with further progress into new technologies added in appropriate increments.

It is also useful to cooperate with other interested parties. Cooperation among public, academic, and private sectors serves to pool available resources, reduce costs, insure compatibility with other technologies on the market, and reduce implementation time frames. Funding requirements can also be reduced by fostering cooperation and spreading costs among other federal, state, and local agencies that are interested in similar technologies.

Most states have not adopted comprehensive new technology programs, but add technologies in a piece-meal fashion, after they have been well tested elsewhere. The state agency survey indicated that most states use CADD extensively and are developing GIS capabilities, but other advanced technologies

are pursued to a much smaller degree. Indiana follows the national trend.

INDOT needs a comprehensive approach to new technologies in order to take full advantage of their benefits. In previous chapters, various technologies were described and evaluated in terms of their expected costs and benefits, and impacts on state transportation agencies. This chapter uses these findings to develop an incremental, phased, advanced technology program. The program is divided into 3 phases: near term (1-3 years), mid term (4-6 years), and long term (7-10 years). Each technology is discussed separately, followed by the development of a general organizational plan to manage all technological applications.

11.1 Computer Aided Drafting and Design

INDOT has used CADD extensively for some time, as mentioned previously. The initial CADD implementation plan has been readjusted and accelerated. A sufficient management structure is in place and significant in-house efforts to further develop the CADD system are ongoing. Therefore, only selected highly focused activities are presented here, that augment and build upon the existing system.

Current Efforts:

- * Demonstration project involving the networking of a remote CADD workstation to the system, with an eventual wide area network (WAN) planned that will extend CADD/GIS capabilities to the districts.

- * Ongoing evaluation, prioritization, and implementation of additional CADD applications in functional areas other than road and bridge design.

Near Term:

- * Development of standards for electronic/digital data exchange between INDOT and design consultants.
- * Special study on entering the Design Standards Details into the CADD system.
- * Developing GDS training modules using DEC windows to serve as a refresher course and for on-line help.
- * A special study on the use of lower cost PC-based CADD/GIS workstations for some applications.

Mid Term:

- * Development and demonstration of expert systems applications to automate certain CADD functions.

Long Term:

- * Automation of many management, engineering, and maintenance functions.

The costs of CADD systems are extensive. However, the high costs are more than offset by the high benefits. A recent TRB study estimated that CADD paybacks take 3-5 years to impact, and that the average payback of CADD in state transportation agencies is 3.6:1 (NCHRP Synthesis 161).

INDOT does not quantify CADD benefits, but estimates that benefits range from 10:1 to less than 1:1 for the various applications used. Current efforts to expand CADD to the districts will extend the high benefits of CADD to the districts. Now that the base system is in place, INDOT also continues to extend CADD by developing applications in areas

other than design, in order to spread CADD benefits to the different functional areas.

The large amount of resources tied up in an extensive CADD system mean that small improvements in productivity can result in large benefits. Several near term projects can improve the productivity of the CADD system.

Creating a CADD standards library containing standard design details and drawings significantly improves the productivity of designers, and was cited by the TRB study (NCHRP Synthesis 161) as an important element of an efficient CADD program. However, the costs are significant as well, as it requires many man-hours of labor. Several options exist for creating a standards library. These include scanning existing drawings, redrawing standards manually using existing labor as time permits, and hiring consultants to redraw the sheets on the system. If scanning is used, time must also be allowed for checking and correcting drawings.

INDOT's Design Standard Details consists of 180 sheets plus some miscellaneous details. Due to the extensive labor costs, a detailed study is required to evaluate and compare each method prior to selecting an alternative. This study would involve determining the manpower, time frame, and costs of each alternative, then comparing to select the best alternative, taking into account the availability of INDOT personnel and the added productivity from completing the library at an earlier date. This study would also set a time

frame and determine the costs and benefits of the library. It would involve the following elements:

- * Obtaining a typical standards sheet.
- * Scanning it to determine the time and manpower required to develop usable drawings.
- * Drawing the sheet to determine the time and manpower.
- * Projecting time and manpower costs for the entire project for both alternatives.
- * Contacting consultants to determine fees and time frames.
- * Interviewing CADD design management to estimate benefits in terms of productivity improvement and determine labor availability.
- * Comparing, selecting an alternative, and generating an implementation plan.

INDOT personnel may already have a feel for the time required to scan and draw the drawings. In this case the first three items would not be needed. The project could be completed by one person in less than two months.

Developing data interchange formats for sharing CADD and survey data with consultants was also cited in NCHRP Synthesis 161 as an important element of a CADD system. This has important GIS ramifications as well. It is especially important to agencies such as INDOT which use consultants extensively.

Various methods exist for transferring data. These include requiring consultants to translate data into the DOT format, accepting various formats from consultants and translating them within the agency, or establishing neutral formats which both the agency and the consultants translate to

and from. Translation software is available, but there are generally some errors in the translation procedures, and data must be rechecked.

States have generally refrained from requiring one vendor specific format be adhered to by all consultants. An exception is Florida, which recently required consultants to prove they could freely translate in and out of the state's IGDS format for an extensive design project. Most states deal with consultants individually, accepting some hard copy and some electronic data. Even Florida still accepts some hard copy. AASHTO and the FHWA are currently developing a neutral format which may be another alternative in future years.

Consultants now use CADD extensively. Setting standards for data exchange would improve the flow of data which would also benefit consultants. Many consultants would be eager to reach data exchange agreements with INDOT. Certain focused activities would help INDOT develop data exchange guidelines.

INDOT CADD management has suggested surveying other DOTs to determine how they exchange information with consultants. This would include designing a questionnaire, sending it out, waiting for replies, possible follow-up phone calls and letters, and compilation of results. It would need to determine how DOTs provide consultants with survey data (electronic, field book, or both), as well as how they receive final designs. A minimum of 6 months would probably be required to conduct such a survey, due to the need to wait for replies.

As an alternative, INDOT could approach consultants to test various methods of data exchange on small projects. Obtaining consultant cooperation would increase the likelihood of success. Information obtained during these projects could be used to determine which methods work best for INDOT. Initially, incentives could be offered to consultants willing to test electronic data exchange procedures when calling for proposals. Time would need to be allowed for checking the accuracy of the data translation and evaluating results.

Designing training modules would also improve the productivity of the system, by allowing operators to receive quick on-line help when they run into problems, and generating a tutorial with which they can refresh their memory and learn more quickly. This would involve attending the GDS training course and interviewing INDOT personnel to determine what aids would be most helpful, developing software tutorials, and documenting the tutorials.

A study on PC-based CADD/GIS workstations would also be valuable. A large proportion of the costs of CADD systems consists of equipment costs. Capabilities of PCs are improving rapidly. Furthermore, for many future applications, such as executive review, screen printing, and making minor data alterations, complete workstation capabilities will not be needed. The Michigan DOT estimates that their "mature" CADD/GIS system will have a much greater number of micro and PC workstations than complete workstations.

An evaluation of PC systems would include an evaluation of the costs and capabilities of existing PC workstations; interviewing functional managers to identify applications where less powerful workstations could be used, estimate the benefits of these applications in terms of labor savings and productivity improvements, determine user requirements, and calculate development costs; and development of an implementation plan including small scale demonstration projects.

These near term projects will improve the productivity of the CADD system, and lay the groundwork for eventual long term automation of many management, engineering, and maintenance functions. INDOT's well established CADD staff is capable of pursuing these projects on their own. In the mid term, INDOT can move towards increased automation by identifying, developing, and demonstrating expert systems applications to automate specific functions. An expert system program is outlined later in the chapter.

11.2 Geographic Information Systems and Advanced Survey Technologies

INDOT is making considerable progress in development of a GIS. Geographical Information Systems are closely related to CADD, and most projects listed as pertaining to CADD affect GIS as well. These projects will improve the productivity of a GIS system in the near term. Consequently, only one near term GIS project is suggested here. In the mid and long terms, GIS can be expected to expand to other applications,

become increasingly automated, and merged with other technologies, as with CADD.

Advanced survey technologies are included with GIS because GIS depend on position data, and the two technologies are closely related. INDOT has recently developed a significant automated survey data collection program.

Current Efforts:

- * Development and implementation of an IDMS/GDS interface.
- * GIS user training.
- * Initial GIS transportation planning pilot project.
- * Additional pavement management systems and roadway inventory applications are planned.
- * Ongoing evaluation and implementation of GIS applications.
- * Cooperation with other agencies to develop base maps.

Near Term:

- * Acquisition of 3 GPS receivers and implementation of GPS for conventional surveying.
- * Tying new projects into the state coordinate plane using GPS and existing NGS monuments.
- * Possible assessment of the information management implications of GIS.

Mid Term:

- * Establishment of a statewide control network based on GPS.
- * Aerotriangulation demonstration project and subsequent implementation.

Long Term:

- * Demonstration of airborne kinematic GPS for photogrammetry

* Automation of many different functions.

The acquisition of GPS receivers for use in conventional surveying has already been proposed within INDOT. Three receivers are necessary to optimize the program. Receivers with the capabilities required by INDOT will cost about \$20,000 a piece. This is an important project. It not only has high potential for increasing survey productivity in the near term, but will lay the groundwork for future developments.

After receivers have been acquired, an intensive training (1-3 weeks) for survey personnel will be required. However, a full year will need to be allowed for learning curve development of an efficient system. At this point, INDOT will need to begin tying all subsequent projects into a state coordinate plane using GPS and existing NGS monuments. This will make the eventual tying of spatial data into a statewide GIS much easier, as compared to revisiting old project sites and redoing control.

This is an interim solution. Eventually, INDOT will need to create a new, more accurate state control network using GPS. This has also been proposed within INDOT, and costs have been estimated at approximately \$300,000. The system will include some existing NGS monuments, plus new monuments. Other agencies such as DNR, county, federal, and private companies would also use the system. Costs can be reduced by fostering communication with other concerned agencies.

Demonstration and implementation of aerotriangulation for photogrammetric control would also significantly increase survey productivity in the near term. This could reduce the amount of field surveying required for photogrammetric ground control by half. However, because of the limited amount of time spent on photogrammetric ground control in INDOT, potential productivity improvements can not be expected to be as great as for using GPS for conventional surveying. Therefore, this project can be put off until mid-term if resources are not immediately available. Eventually, after GPS has been used successfully, airborne kinematic GPS can be applied to photogrammetry as well.

An assessment of the information management implications of GIS may also be beneficial. Many states have found that a large amount of GIS benefits are related to improved data management capabilities that allow reduction of redundant efforts and better communication between various users of the system. Data collection, conversion, integrity checks, updating, storage, communication, security, duplication, quality, accuracy, and interagency sharing all need to be addressed. A special study on data management might improve the productivity of a GIS and determine the number of personnel needed to manage data. This, however, will not be needed if INDOT adds applications gradually, and has personnel available to deal with data management issues as they arise.

11.3 Expert Systems

Although expert systems are not as widely used in state transportation agencies as some other technologies, several leading states in the application of advanced technologies are vigorously pursuing expert systems, and a variety of transportation engineering applications have been developed in recent years. These systems can be interfaced with databases, PMS, CADD, traffic signal controllers, and other systems. They can significantly improve the efficiency and productivity of many agency functions by automating complex time consuming tasks, providing increased capabilities, providing training and advice, and making up for scarcity of experts. Initial reports on the benefits of expert systems have been very favorable. An expert system program is outlined here that would allow INDOT to start slowly, taking advantage of expert systems to increase productivity in the near term while making steps toward long term automation of many functions.

Near Term:

- * Conduct department wide survey of functional managers and develop a long range expert systems plan.
- * Establish an expert systems resource group using personnel from various INDOT units.
- * Develop the initial demonstration projects selected in the long range plan.
- * Initial training of members of the resource group.

Mid Term:

- * Ongoing implementation of expert systems applications as identified in the long range plan.

- * Shifting of expert systems training and development to in-house, as overseen by the resource group.
- * More advanced applications such as CADD supplements, real-time traffic adaptive signal control for IVHS, engineering training, and robotics.

Long Term:

- * Automation of many engineering, management, and maintenance functions, and merging with a variety of other advanced technologies.

A long range plan is needed to insure the success of a new technology program. Interviews will be a useful tool in the development of a long range expert systems plan. Interviews with the functional heads will be used to:

- Familiarize functional heads with expert systems.
- Gain the confidence, support, and input of future users.
- Identify applications with high potential for automation, preservation of scarce knowledge, and improved productivity.
- Identify the nature of the applications, including:
 - Existing computer environments
 - Problem definitions
 - System inputs and outputs
 - Nature and number of users
 - Potential benefits in terms of productivity
 - Availability of experts.

The long range plan will present an implementation schedule based on this information. Applications will be ranked according to potential benefits, ease of implementation, and potential for high user support. This will identify initial demonstration projects. Starting with small scale PC-based applications is recommended in order to prove the technology and gain experience prior to committing

large amounts of resources. PC-based expert system shells are inexpensive, and capabilities are improving rapidly. The plan should also specify a computer environment for delivery of the initial demonstration systems. It should be completed within 6 months.

Initial projects can be contracted out to consultants or the universities, while INDOT is gaining experience. The initial contracts should also cover initial training of key management personnel. The first projects should be completed within two years.

Key management personnel should be identified prior to the development of initial systems. Eventually, an artificial intelligence management group will be needed to transfer technology, train users, reevaluate the plan, develop additional applications, and maintain quality control. The size of this group should be relatively small. The personnel will be trained during development of the initial systems.

In the mid-term, this group will take over ongoing implementation, shift training to in-house, and determine the number of additional personnel needed. Mid-term projects will be of increased complexity and merged with other technologies, such as real time signal control for IVHS, automated CADD/GIS functions, training of engineers, and robotics. In the long term, expert systems will provide for increased automation of a variety of functions.

11.4 Computer Technology in Planning and Programming

The INDOT has not been a heavy user of computer technology in its planning and programming efforts. Much progress has however taken place in recent years and many of the planning and programming functions are being automated. A great deal of effort has been made in preparing computerized road inventory and traffic inventory data bases. Current efforts are underway in updating existing computer models and acquiring new packages to perform various planning and programming functions. Suggestions for a phased program of actions that can be pursued in making use of computer technologies in these functions are presented below.

Near Term Efforts:

- * An assessment of current use of automated data bases and identification of future needs.
- * Updating of computer models for metropolitan planning and impact analyses of projects, including environmental analyses.
- * Training of planning and programming personnel at INDOT as well as at local agencies.
- * Provision of leadership and guidance to local planning agencies, particularly in metropolitan areas on the use of computer technology.

Mid-Term:

- * Coordination of updating efforts in cooperation with local agencies.
- * Development of capability of performing in-house environmental analyses on a macro as well as on a micro level.
- * Development of capability of generating computerized information from congestion, safety, and public transportation rolling stock management systems as well as information on condition and other items from pavement and bridge management systems, delivering appropriate

input to programming decisions.

Long Term:

- * Development of a multimodal transportation planning tool for statewide applications.
- * Development of a multimodal programming tool for the allocation of available funds.
- * Development of an integrated planning, programming and budgeting model using various computerized data bases, management systems, revenue forecasting tools and transportation planning forecasts.
- * Long range human resource development in the area of planning and programming.

11.5 Quality Assurance in Construction

INDOT should pursue the development of a quality assurance program as a part of its automated construction data management system. The development of software for QA could be performed in a PARADOX format or some other compatible format which can be easily converted. This development of the automated QA system should be subject to the constraints and requirements of the automated construction data system (i.e. degree of field automatation, types and limitations of hardware components, etc.). INDOT should also make the QA specifications part of the standard specifications that are to be used throughout the state. The QA involvement in INDOT at present should remain in the areas of pavement, structural concrete, and aggregates; other areas (such as embankments, bases, etc.) could be added after proper development of QA standards and from feedback from other states.

It is recognized that the changes in conducting practices necessary to adopt life cycle based cost and performance considerations in contractor selection are not trivial and much careful evaluation will be required. However, the use of computer technologies can greatly facilitate the process.

Short Term

- Automate the bituminous quality assurance program for use in all INDOT districts.

- Implement and automate QA system for both PCC pavements and structural concrete.

Mid Term

- Develop and implement QA standards for other areas of concern such as aggregates, embankments, bases, etc.

- Investigate the use of QA "checklist" standards to complement the quantitative standards already being practiced.

Long Term

- Integrate QA system fully into the final automated construction data management system.

- Consider the adoption of a life cycle based cost and performance evaluation procedure in contract management.

11.6 Robotics and Automation

Although the use of robotics and automated equipment may not be justified at present, INDOT should explore the potential of using such devices in the mid and long terms. With a receptive attitude towards advanced automated construction and maintenance equipment, INDOT can even

position itself to enter into partnership with contractors and private entrepreneurs in the development of innovative equipment. An example of such a partnership is Caltrans' current work on automated pavement crack filler. Another action on the part of INDOT can be to enter into a regional program of technology transfer in cooperation with other adjoining state agencies, so that recent advancements in robotics and automation can be applied to roadway construction and maintenance. If applied appropriately, automation can reduce labor costs, remove or reduce safety risks, increase productivity, and establish better control over product/work quality. Automation of work processes within the field of roadway construction and maintenance has enough potential to warrant interest and action by both government and industry. Efforts should be made to bring both parties together to foster growth and application. A possible set of actions that can be taken in this area is noted below:

Near Term Efforts:

- * Establish an evaluation group within INDOT to review possible applications of robotics in the construction field and encourage contractors to use automated equipment.
- * Encourage the establishment of a regional technology development program to assist private and public sectors in the rapid deployment of robotic applications in roadway construction and maintenance activities.

Mid Term:

- * Develop or acquire numerically controlled or partially autonomous equipment for construction and maintenance activities.

- * Acquire automated road and bridge condition assessment devices.

Long Term:

- * Develop or acquire fully autonomous equipment to meet some specific needs of INDOT's construction and maintenance activities.

All levels of automation should be investigated for use. However, because automation within roadway construction and maintenance is in its infancy, numerically controlled and partially automated applications may be the best approach to take in the mid term. Such measures would be the least expensive and yield a more rapid return on investment which would encourage its growth. An example is the laser-guided, microcomputer grading system. Another possibility is soil compaction. For a desired level of compaction in soil, an automated device can be developed between a vibratory roller and a nuclear density meter. With a microprocessor on board the roller, radio feedback between the density meter and the roller could adjust the speed of the roller, the magnitude of vibration, and the number of passes necessary. Another example would be for bituminous paving. A microcomputer on board the paver could accurately determine and adjust for the exact pre-compaction thickness of the bituminous course by considering the mix design, the final post-compaction thickness, and the types of vibratory rollers used. These examples indicate an area of great potential for automation; other potential applications could be focused on cut and fill

operations, base preparation and placement, pavement placement, curbing and guardrail/retaining wall placement, and maintenance (Skibniewski and Hendrickson 1990). The attainment of quality control can be achieved on a project-wide level by means of the designated parameters which are common in many roadway projects. Another advantage would be that the degree of automation needed for the above list of projects could be achieved by simply modifying existing equipment. This would reduce development costs and retail costs to interested contractors. This in turn would make automated equipment readily available to most contractors fostering the growth and interest in automated construction and maintenance.

11.7 Intelligent Vehicle/Highway Systems

INDOT is making considerable progress in IVHS in relation to an FTMS on the Borman Expressway and an extensive permanent WIM program. The Borman FTMS is in the design and initial implementation stages. Many activities are already occurring, and many additional near term activities are planned. The Borman FTMS managers have become proficient with IVHS technologies and are actively communicating with other parties, such as the adjacent Chicago Area FTMS personnel, the FHWA, Purdue University, and private companies. Many near and mid term activities are presented here that will incrementally build on current efforts and move toward long range goals.

Current and Planned Activities:

- * Initial traffic data collect using portable WIM and AVC.
- * Design of inductive loop surveillance system for incident detection and traffic monitoring.
- * Implementation of incident response patrols to quickly respond to incidents.
- * Development of a freeway simulation model with Purdue University.
- * Implementation and testing of Changeable Message Signs to provide driver information to users.
- * Development of Detour Contingency Plans to reroute traffic around congestion.
- * Development of an improved incident detection algorithm .
- * Communication with the adjacent Chicago Area FTMS management to work out methods of coordinating efforts and sharing data between the two systems.
- * Planned wide area radio communications network to transmit detector data.
- * Planned purchase of WADS detectors to be used in the calibration of loop detectors.
- * Planned development of a traffic operations center (TOC) to initially be used for data collection and eventually monitor and control the system.
- * Planned extension of ATMS to the closed loop signal systems on adjacent arterials to coordinate them with rerouted freeway traffic. Ramp metering may also be used.
- * Investigation of compressed video for sending WADS images to the TOC.

Additional Near Term Activities:

- * Special study on the management of WIM/AVC data.
- * Demonstration of AVI.
- * Applying ATMS to other freeway corridors and urban arterial networks in selected locations.

Mid Term:

- * Development and demonstration of adaptive real time signal control using expert systems.
- * Demonstration of ADIS on the Borman.
- * Demonstration of AVI and WIM for truck traffic monitoring.
- * Expansion of FTMS to other corridors.
- * Possible demonstration of satellite communications.
- * Demonstration of the integration of GIS into the Borman FTMS to provide base maps for ADIS in-vehicle navigation aids and graphically monitor the system.

Long Term:

- * Comprehensive statewide WIM/AVI program for heavy vehicle monitoring.
- * Integration of ADIS and ATMS into corridorwide systems.
- * Extensive use of AVI for toll collection and congestion pricing.

A study on WIM and traffic data management is a high priority project. Currently traffic data is difficult to access in a usable format by the various divisions. The traffic volume, classification and weight data are important inputs to many engineering and planning functions. In order to make portable WIM data more useful and insure the new WIM/AVC program serves its purposes, resources need to be assigned to this project immediately. This study should include identification of all users, identification of the data and formats required by users, identification of all traffic data collection activities and equipment, and development and demonstration of methods for transferring data between the data collectors, the database and the users. It

should also address translation to required FHWA formats. Possibly, additional personnel from information management or other divisions that are proficient with computers could be assigned to the project, if needed.

Additional near term projects include an AVI demonstration project and the application of ATMS to urban arterials. Demonstrating AVI will lay the foundation for future comprehensive use of AVI throughout the state, and in coordination with other states, to monitor heavy vehicles, track hazardous materials, and improve traffic flow through congestion pricing and automatic toll collection. Several options exist for an AVI demonstration project, including, automatic toll collection, congestion pricing, and truck monitoring. However, it must be remembered that if congestion pricing is investigated, strong lobbying of the public will be needed before it can be implemented (Daniel et al. 1990). Legal barriers may exist to AVI for truck monitoring as well.

The use of AVI systems is not limited to trucks and other commercial vehicles. A primary area of application is for electronic toll collection, such as on the Indiana Toll Road. Installing such systems has the potential for eliminating queues at toll booths, hence reducing travel times and increasing safety on toll roads. These systems have the added benefit that additional traffic may be shifted to the toll road, if the travel times are reduced substantially as a result of AVI, or other electronic toll collection systems.

The major obstacle to the use of AVI systems for private automobiles has been their perceived intrusion of the privacy of users. However, past studies have shown that the traveling public may be willing to trade off this disadvantage for the added convenience of electronic toll collection.

It is therefore, critical that a comprehensive market research effort be performed prior to implementing an AVI system on the Indiana Toll Road. Such a research must be able to evaluate the public's willingness-to-pay for different electronic toll collection systems (AVI, Debit Cards, and others) in order to recommend the use of the most appropriate technology, if any.

There are several possible partners that could be included in the near term demonstration projects (Figure 11.1). INDOT should begin dialogue with these parties to determine what type of projects they would be willing to participate in and help fund. The Intermodal Surface Transportation Efficiency Act of 1991 has provided sizable funds for IVHS demonstration projects in the next few years. In addition, an effort should be made to communicate with adjacent states. Several border states are involved in the Advantage I-75 project to monitor heavy vehicles using WIM and AVI on the I-75 corridor. In the future, states will need to coordinate AVI activities to allow the sharing of truck data and insure equipment compatibility, and INDOT should begin this process now.

| TECHNOLOGY | POSSIBLE DEMO TYPES | TIME FRAME | POSSIBLE LOCATION | POSSIBLE PARTNERS |
|---|---|------------|--------------------------------|--|
| AUTOMATED VEHICLE IDENTIFICATION (AVI) | TRUCK REGULATION ENFORCEMENT TOLL COLLECTION CONGESTION PRICING ELECTRONIC LICENSE PLATE | 1992 - 94 | NW INDIANA INDIANAPOLIS | <ul style="list-style-type: none"> • INDOT • FHWA • LOCAL GOVERNMENTS • AUTOMOTIVE INDUSTRY • ELECTRONIC INDUSTRY • COMPUTER SOFTWARE INDUSTRY • IMTA • AAA • OTHERS |

Figure 11.1: Near Term Demonstration of AVI.

It must be remembered that if congestion pricing is investigated, strong lobbying of the public will be needed before it can be implemented (Daniel et al. 1990). Legal barriers may exist to AVI for truck monitoring as well, and the cooperation of truck user groups will need to be obtained.

ATMS for urban arterials should also be initiated in the near term, perhaps through a demonstration project in a selected urban area. The Greenfield and Laporte Districts already have closed loop computerized monitoring of signals, and Evansville and Fort Wayne have had centralized signal control using mainframes. One of these areas could be selected, or an area that will be included in a future FTMS corridor could be used. An ATSAC-type system which is based on mainframes could be initiated in the Greenfield or Laporte districts, which have experience with mainframe based systems.

INDOT is planning to test remote altering of signal timings around the Borman to accommodate rerouted traffic. There are already closed loop signal systems on the adjacent arterials. Alternatively, the initial demonstration of ATMS for urban arterials could be conducted in this area, by expanding the scope of the project to include recent ATMS developments.

ATMS software packages have been developed that allow traffic responsive traffic control using networked PC workstations, which are thus much cheaper than older UTCS mainframe based systems (Haver and Tranoff 1991). In the

mid-term, the ATMS and FTMS on the Borman can be completely integrated.

Several other projects can be initiated in the mid-term to build on current efforts. Demonstrating ADIS on the Borman FTMS is one such project. This is the first step in eventual integration of ATMS and ADIS into corridorwide IVHS systems, and should be conducted after the implementation of the Borman project. Another potential area of application for ADIS is the Indianapolis area, where the possibility of reducing congestion through improved information is substantial. INDOT will need to seek outside assistance for these projects. The cooperation of the automotive industry is necessary in testing ADIS, and the FHWA and other possible partners may be willing to assist as well. INDOT should also seek to coordinate the demonstration with adjacent states. Chicago and Michigan are currently involved in extensive ADIS demonstration projects.

A critical step in the evaluation of ADIS for any road network is to investigate the possibility of negative impacts of information on travel times. This problem may arise if all drivers are given the same information and react in a similar manner by shifting simultaneously from the congested routes to the uncongested routes, hence effectively transferring congestion from one part of the network to another.

To guarantee that such behavior does not happen, the information provided to the drivers must be designed carefully and a thorough investigation of drivers' response to information must be performed. Such an investigation can be

the focus of a research program that should also include the development of network performance prediction methods, under different information provision scenarios. The result of such a research program would be the recommendation of a specific ADIS design and configuration.

A research program along the above mentioned lines could be implemented for the Borman expressway corridor and/or for the Indianapolis metropolitan area. This would allow INDOT to use the best configuration of ADIS for each of these locations.

After the Borman FTMS is implemented, what was learned can be applied in other areas. Three high traffic areas that are candidates for future ATMS expansion include: the I-65 corridor near Louisville, Kentucky; The I-65 corridor in Indianapolis; and an expansion of the Borman FTMS eastward on I-94 to the Michigan Border, including parts of I-65 and US 30, to create a corridor wide ATMS.

As IVHS activities begin to spread over larger distances, satellite communications may become a more feasible option. The costs of these systems are high at present, but a mid-term demonstration of the technologies should not be ruled out. They can transport data over larger distances without increasing costs.

The joint use of AVI and WIM for truck traffic monitoring can also be demonstrated in the mid term, after an initial AVI demonstration and the implementation of the WIM/AVC program are completed. This will help move towards a comprehensive

statewide program, and will require coordination between a variety of partners.

Finally, two mid term projects can be undertaken internally. After INDOT has developed an expert systems program, appropriate routines can be developed to aid in ATMS. Possible applications include training of TOC personnel, traffic responsive signal control, and selecting responses to incidents.

GIS can also be useful if integrated into ATMS (Albert et al. 1990). Computerized maps can be used in the TOC to display traffic conditions, incident locations, alternate routes, CMS locations, locations of emergency response vehicles, locations of maintenance and construction activities, and other data. In addition, base maps may be required for computerized in-vehicle navigation systems, which can be taken from the GIS.

In the long term, these activities will move towards a comprehensive WIM/AVI program for heavy vehicle monitoring, integration of ADIS and ATMS into corridorwide systems, extensive use of AVI for toll collection and congestion pricing, and eventual integration of automatic vehicle control technology into an automated highway system. It is important that INDOT continue to actively communicate and coordinate activities with other partners to help move towards these long term goals. An effort should be made to have appropriate personnel involved from the beginning, in addition to the personnel that are gaining experience on the Borman FTMS now,

so that they can be the future managers of IVHS efforts within Indiana.

11.8 Program Management

It is important for INDOT to consciously decide how it will approach new technologies. That decision will determine which technologies will be implemented, and when they will be implemented.

It is not merely a matter of selecting promising new technologies individually. Rather, the key issue is how to take full advantage of the agency's resources. A comprehensive new technology program can help INDOT systematically evaluate and implement new technologies, while optimizing the use of resources and providing flexibility to deal with future developments.

After deciding which approach to take in implementing advanced technologies, INDOT must contend with the barriers. The first possible barriers are probably the general resistance against change and difficulty in quantifying potential benefits to justify high capital costs. However, with a formulated approach to new technologies, these problems can be reasonably addressed.

Personnel must also be trained to use the new technology and remain abreast of emerging developments. Unless the transportation agencies recognize the importance of advanced technologies and commit resources to train personnel, much of the implementation effort will be in vain (Sinha et al. 1988).

A program of continuing education is needed to keep transportation personnel up to date. INDOT therefore needs to consider how it can develop appropriate human resources to manage its efforts in adopting new technologies.

Furthermore, to implement an advanced technology application, it must be viewed as having a favorable cost/benefit ratio. This is a question that should be tested by each state, perhaps by an intradepartmental committee or a task force. For INDOT, such a task force exists in the area of data processing and computational resources. It may be necessary to set up similar task forces to deal with specific advanced technology applications.

Any major technological innovation contemplated for application should be analyzed using an evaluation framework. A possible outline of this framework is given below:

1) Life Cycle Costs

- Design
- Development
- Installation
- Operation and Maintenance

2) Effects on Agency Performance

- Reduction in Personnel time
- Improvements in quality of work
- Fostering better communication in the agency
- Reduced paperwork
- Improved data storage and retrieval
- Improved public interface
- Accountability and better control
- Better utilization of resources
- Improved human resource development
- Improved legislative interaction

3) User Benefits:

- Reduction in travel time
- Savings in operating cost
- Safety improvements
- Improved productivity in the transportation industry

4) Statewide Impacts:

- Improved environmental quality
- Conservation of energy
- Fostering of economic development
- Facilitating public/private cooperation
- Fostering federal/state/local cooperation

5) Implementation Characteristics

- Impact timing
- Compatibility with other efforts
- Legal requirements
- Public acceptance
- Possibility of federal, private, and other support

For continuing involvement, a new technology application group should be created. This group could be located preferably within the research division. This group would be small at first, and the division could gradually be transformed into a research and new technology division. The group, in cooperation with the appropriate personnel from other divisions, would develop an initial long range plan and evaluate, select, and implement new technologies.

The technology group must keep abreast of new developments and foster communication with the universities, the private sector, other state agencies, and the federal government. One method for accomplishing this would be to allocate the responsibilities to one person, placed on half time. This person would subscribe to relevant publications, periodically review literature, and report to the new technology group. As intradepartmental task forces are formed in the various technology areas, and the members of the task forces become increasingly involved in the new technologies,

these responsibilities can be shifted to the functional managers of the divisions involved. For example, in INDOT, the LaPorte District Operations Engineer responsible for Borman Expressway project now spends considerable time communicating with private companies and with other state DOTs.

Training operational managers takes considerable resources, and once they are trained their expertise should not be wasted. These people need to periodically interact with the new technology group. The new technology group should also periodically meet with outside experts, such as university researchers, their counterparts from other states and industry representatives, to augment their efforts. Joining new technology organizations and attending conferences also helps to foster communication and keep the department informed.

The INDOT must strive for cooperation with the various parties involved in advanced technologies (Figure 11.2), including cooperation within the department. Communication and involvement with future users of the system is necessary. For example, expert systems will not be accepted by the users unless they have confidence in and understand the system. The new technology group will be responsible for training users, and gaining their input prior to system design.

One technique commonly used to involve users in the process is intradepartmental interviews. Interviews can be used to familiarize future users and managers with the

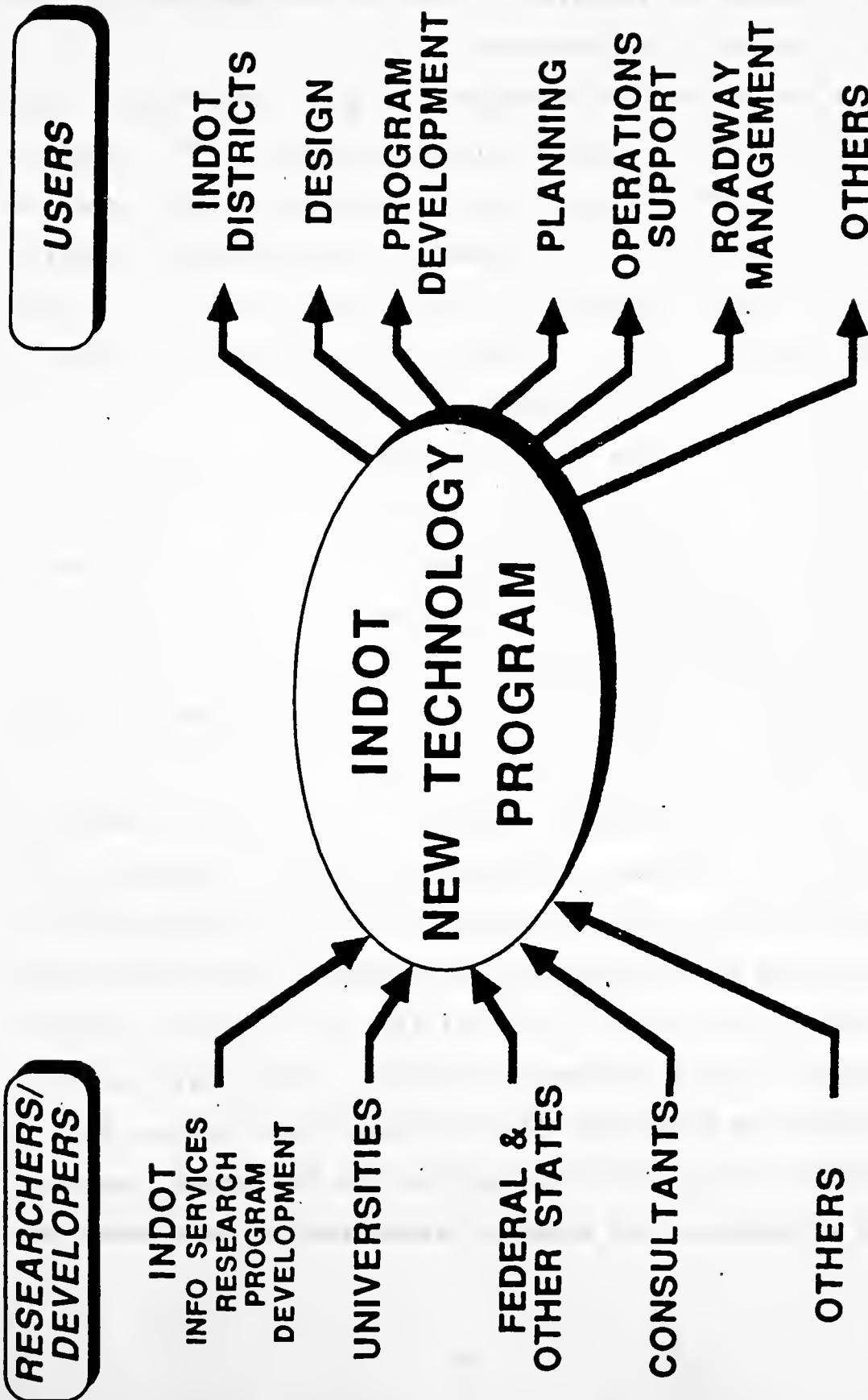


Figure 11.2: Parties Involved in a New Technology Program.

technology, identify applications with high potential, quantify potential benefits, determine user requirements, and identify existing environments.

In some cases, the managers will also need to coordinate activities with the public and users groups. For example, testing AVI for truck traffic monitoring will not be successful without the involvement of the trucking industry, and AVI for congestion pricing would require public interaction to convince users that its benefits outweigh restrictions on their liberties.

Initially, members of the new technology group may lack expertise in a given area. In these cases, consultants, universities, and other sources will need to be employed while the staff gains experience. It is useful to start with small scale demonstration projects while personnel gain experience with a system. Personnel trained in these demonstrations can then be responsible for training future users.

The INDOT management needs to be aware of possible impacts of advanced technologies on its organizational framework and internal functions. As new technologies are incorporated into the agency, procedures will be changed, and resources will need to be shifted from labor intensive procedures to more automated procedures. This may require a realignment of divisions and other operational units. Such a realignment would involve generating new job titles, changing salary structures, and altering procedures, to take advantage

more efficiently of the opportunities provided by emerging technologies.

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APPENDIX A: A COPY OF SURVEY QUESTIONNAIRE.

1

Questionnaire

USE OF ADVANCED TECHNOLOGIES IN TRANSPORTATION AGENCIES

1. a) Agency:
b) Name and telephone number of person completing questionnaire:
2. Which statement best characterizes your agency?
 - a) We have already applied some advanced technologies (see examples in Question 3 below).
 - b) We are planning to apply some advanced technologies.
 - c) We have no current plan to apply advanced technologies.
3. Please describe on a separate sheet any research and development projects in your organization involving the following technologies:
 - a) Computer Applications
 - b) Robotics in Construction and Maintenance
 - c) Intelligent Vehicle/Highway System
 - d) Automatic Vision and Image Processing
 - e) Real Time Traffic Control
 - f) Expert Systems
 - g) GIS
 - h) Others (please specify)

4. Please check the areas in which your agency is currently using or planning to use computer and advanced technologies. Please also indicate the levels of costs and benefits that can be expected from the use of these technologies in the areas, listed below, in your agency:

| | Cost of Use | | | Benefit of Use | | | No Plan to Use |
|--|-------------|-----|------|----------------|-----|------|----------------|
| | High | Low | None | High | Low | None | |
| a. Data Base Management | | | | | | | |
| b. Automated Pavement and Bridge Distress Sensing System | | | | | | | |
| c. Travel Monitoring and Counting | | | | | | | |
| d. Arterial Traffic Operations and Management | | | | | | | |
| e. Highway Information Systems and User Communications | | | | | | | |
| f. Computer Aided Planning and Design | | | | | | | |
| g. Laboratory and Field Data Collection and Analysis | | | | | | | |
| h. Construction Management and Quality Control | | | | | | | |
| i. Advanced Survey Positioning System | | | | | | | |
| j. Others (please specify) | | | | | | | |
| _____ | | | | | | | |
| _____ | | | | | | | |
| _____ | | | | | | | |

5. For those items in 4 which were checked, please briefly describe how computer and advanced technologies are being used by your agency. (Use separate sheets, if necessary).

6. What other areas do you feel have potential for application of computer and advanced technologies?

7. What do you perceive as possible barriers against the use of computer and advanced technologies in your agency? (Please check the appropriate items).

- a) High initial cost
- b) High operation and maintenance cost
- c) Lack of trained personnel
- d) Uncertainty about potential benefits
- e) Fear of labor displacement
- f) Lack of provisions in contract agreements
- g) General resistance against change
- h) Uncertainty about the type of technologies that can be used
- i) poor training and support offered by vendors
- j) If you wait, even more advanced systems will be available next year
- k) Others (please specify):

Please mail the completed questionnaire to Kumares C. Sinha, School of Civil Engineering, Purdue University, W. Lafayette, Indiana 47907. Thank you very much for your kind cooperation.

APPENDIX B: BORMAN EXPRESSWAY DELAY CALCULATIONS

Assumptions:

- * Blocking a single lane of a 3-lane freeway reduces capacity by 50% (Minnesota DOT 1982, TRB Circ. 326 1986).
- * Blocking two lanes reduces capacity by 70% (TRB Circ. 326 1986).

Scenario 1:

- * A westbound vehicle stalls in the shoulder lane just east of the state border at 8:00 am, blocking 1 lane.
- * Without a detection system, it takes 30 minutes for the incident to be cleared (Cassidy 1990). With an incident detection and response system it takes 15 minutes.
- * Traffic volume at 8:00 am: 3,635 vehicles per hour (vph) (HNTB 1989).
- * Capacity is 5,000 vph (HNTB 1989), which reduces to 2,500 vph during the incident.

Scenario 2:

- * An incident as in scenario 1 occurs between Cline Avenue and Burr Street in the eastbound direction at 4:00 pm.
- * Volume is 4,855 vph from 4:00 pm to 5:00 pm, and 4,370 vph from 5:00 pm to 6:00 pm (Cassidy 1990).
- * Capacity is 5,200 vph (HNTB 1989), which reduces to 2,600 vph during the incident.

Scenario 3:

- * A major incident occurs at the same location and time as scenario 2, and blocks both the shoulder and middle lanes for 1 hour (Cassidy 1990), which is reduced to 45 minutes by an incident detection and response program.
- * Capacity reduces to 1,650 vph during the incident (Cassidy 1990).
- * Volumes further reduce to 3,933 vph from 6:00 to 7:00 pm, and to 3,545 vph after 7:00 pm (Cassidy 1990).

Delay Calculations:Scenario 1:

Total Duration of Congestion (T):

$$3635 \text{ vph (T)} = 2500 \text{ vph (0.25 hr)} + 5000 \text{ vph (T - 0.25 hr)}$$

$$T = 0.46 \text{ hr} = 27 \text{ minutes}$$

Maximum Queue Length (8:15 am):

$$3635 \text{ vph (0.25 hr)} - 2500 \text{ vph (0.25 hr)} = 284 \text{ vehicles}$$

Total Delay (TD):

$$1/2 (0.46 \text{ hr}) (284 \text{ veh}) = 64.9 \text{ vehicle-hours}$$

Scenario 2:

Total Duration of Congestion (T):

$$4855 \text{ vph (1 hr)} + 4370 \text{ vph (t)} =$$

$$2600 \text{ vph (0.25 hr)} + 5200 \text{ vph (0.75 + t hr)}$$

$$t = 0.37 \text{ hr}$$

$$T = 1 + t \text{ hr} = 1.37 \text{ hr}$$

Maximum Queue Length (4:15 pm):

$$4855 \text{ vph (0.25 hr)} - 2600 \text{ vph (0.25 hr)} = 564 \text{ vehicles}$$

Queue Length at 5:00 pm:

$$4855 \text{ vph (0.25 hr)} - 2600 \text{ vph (0.25 hr)} - 5200 \text{ vph (0.75 hr)} \\ = 305 \text{ vehicles}$$

Total Delay (TD):

$$1/2 (0.25 \text{ hr}) (564 \text{ veh}) + 1/2 (564 + 305 \text{ veh}) (0.75 \text{ hr}) + \\ 1/2 (305 \text{ veh}) (0.37 \text{ hr}) = 452 \text{ vehicle-hours}$$

Scenario 3:

Total Duration of Congestion (T):

$$4855 \text{ vph (1 hr)} + 4370 \text{ vph (1 hr)} + 3933 \text{ vph (1 hr)} + 3545 \text{ vph (t)} = 1650 \text{ vph (0.75 hr)} + 5200 \text{ vph (2.25 + t hr)}$$

$$t = 0.13 \text{ hr}$$

$$T = 3 \text{ hr} + t = 3.13 \text{ hr}$$

Maximum Queue Length (4:45 pm):

$$4855 \text{ vph (0.75 hr)} - 1650 \text{ vph (0.75 hr)} = 2404 \text{ vehicles}$$

Queue Length at 5:00 pm:

$$2404 \text{ veh} - [(5200 - 4855 \text{ vph}) (0.25 \text{ hr})] = 2318 \text{ vehicles}$$

Queue Length at 6:00 pm:

$$2318 \text{ veh} - [(5200 - 4370 \text{ vph}) (1 \text{ hr})] = 1488 \text{ vehicles}$$

Queue Length at 7:00 pm:

$$1488 \text{ veh} - [(5200 - 3933 \text{ vph}) (1 \text{ hr})] = 221 \text{ vehicles}$$

Total Delay (TD):

$$1/2 (0.75) (2404) + 1/2 (0.25) (2404 + 2318) +$$

$$1/2 (1) (2318 + 1488) + 1/2 (1) (1488 + 221) +$$

$$1/2 (0.13) (221) = 4262$$

$$TD = 4,262 \text{ vehicle-hours}$$

